Industrial Thermal Insulation An Assessment

R. G. Donnelly
V. J. Tennery
D. L. McElroy
T. G. Godfrey
J. O. Kolb

NOTICE

PORTIONS OF THIS REPORT ARE ILLEGIBLE. It
has been reproduced from the best available
copy to permit the broadest possible avail-
ability.

MASTER

OAK RIDGE NATIONAL LABORATORY

OPERATED BY UNION CARBIDE CORPORATION FOR THE ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22161
Price: Printed Copy \$7.75; Microfiche \$2.25

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

Contract No. W-7405-eng-26

METALS AND CERAMICS DIVISION
ENERGY DIVISION

INDUSTRIAL THERMAL INSULATION — AN ASSESSMENT

R. G. Donnelly, V. J. Tennery, D. L. McElroy,
T. G. Godfrey, and J. O. Kolb

Prepared for
Division of Buildings and Industry,
Energy Research and Development Administration

MARCH 1976

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830
operated by
UNION CARBIDE CORPORATION
for the
ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED *EP*

**THIS PAGE
WAS INTENTIONALLY
LEFT BLANK**

FOREWORD

In keeping with the objectives given in *A National Plan for Energy Research, Development and Demonstration*, the more effective utilization of thermal insulation within the industrial sector has been identified as a potential program area for energy conservation. To better define the potentials of this program area, the Metals and Ceramics Division of Oak Ridge National Laboratory was selected to:

1. identify potential savings of energy available through use of insulation in the various elements of the industrial sector,
2. assess the status of insulation technology,
3. identify areas within the insulation technology that require additional research and development effort.

Assessment of the status of the insulation technology was undertaken from three viewpoints: the technological viewpoint (ORNL assessment); the manufacturer's viewpoint, and the user's viewpoint. The results of the assessment, as given in this volume, will be presented for public appraisal and comment on March 24, 1976, at Oak Ridge, Tennessee. A summary of this meeting is to be published as a supplement to this report. The final result is expected to represent a factual assessment of industrial insulation technology and to provide direction for energy conservation programming in both the public and private sectors.

R. W. Anderson
Division of Buildings and Industry
Energy Research and Development Administration

ACKNOWLEDGMENTS

Many people have contributed to the work described in this report. However, the authors wish to particularly thank R. W. Anderson of ERDA's Division of Buildings and Industry, and W. C. Turner, consultant, who provided critical early guidance, and to all those whom we contacted and who provided us the information to prepare this assessment. In addition, the authors would like to thank the following persons for reading and commenting on the text of the report:

W. C. Turner, South Charleston, West Virginia

Hayne Palmour III, North Carolina State University

R. P. Tye, Dynatech R/D Company

C. M. Pelanne, Johns-Manville

J. P. Moore, ORNL

J. T. Meador, ORNL

D. R. Johnson, ORNL

We express our appreciation to Frances Scarboro, Gail Smith, and Carol Carter for their expertise in typing and assembling the first draft of this report under rushed conditions. Finally, we wish to express our deep appreciation to those who, after nearly all the time had run out, managed to speed the final preparation and dissemination of this report as required for the workshop scheduled in March. These include:

Sig Peterson, Technical Editor, the staff of the Metals and Ceramics Division Reports Office headed by Meredith Hill, the staff of the ORNL Reproduction Department under Brena Stevens, and Lowell Langford of the Laboratory Records Department.

CONTENTS

FOREWORD	iii
ACKNOWLEDGMENTS	iv
LIST OF FIGURES	vii
LIST OF TABLES	xi
SUMMARY	xiii
1. INTRODUCTION	1
2. CONCLUSIONS AND RECOMMENDATIONS	3
2.1 CONCLUSIONS	3
2.1.1 Assessment of Available Industrial Thermal Insulation Materials	3
2.1.2 Assessment of Economic Considerations	4
2.1.3 Assessment of Heat Transmission Information	5
2.2 RECOMMENDATIONS ON MATERIALS AND APPLICATION	6
2.2.1 Low Temperatures	7
2.2.2 Intermediate Temperatures	7
2.2.3 High Temperature Range	8
2.3 ECONOMIC RECOMMENDATIONS	9
2.4 RECOMMENDATIONS ON PROPERTY DETERMINATIONS	9
3. ASSESSMENT OF AVAILABLE INDUSTRIAL THERMAL INSULATION MATERIALS	11
3.1 ASSESSMENT AND DISCUSSION OF AVAILABLE INSULATION MATERIALS	11
3.1.1 Cryogenic Range	11
3.1.2 Low Temperature Range	15
3.1.3 Intermediate Temperature Range	17
3.1.4 High Temperature Range	18
3.2 ENERGY CONSERVATION POTENTIAL OF THERMAL INSULATIONS	22
3.2.1 Immediate-Term Conservation Considerations	27
3.2.2 Near-Term Conservation Consideration	28
3.3 OBSERVATIONS FROM INSULATION MANUFACTURERS, INSULATION USERS, AND EQUIPMENT AND SYSTEM DESIGNERS	28
3.3.1 Industrial Chemicals	30
3.3.2 Primary Metals (Steel and Aluminum)	33
3.3.3 Petroleum Industry	35

3.3.4	Paper Industry	36
3.3.5	Architect-Engineering (A-E) Firms	37
3.3.6	Cement Industry	38
3.3.7	Glass Industry	39
3.3.8	Food Industry	40
3.3.9	Electric Power Utilities	41
3.4	SUMMARY OF TECHNICAL PROBLEMS.	41
3.5	REFERENCES	44
4.	ASSESSMENT OF ECONOMIC CONSIDERATIONS	45
4.1	INTRODUCTION	45
4.2	BACKGROUND FACTORS AFFECTING INSULATION USE	45
4.3	ASSESSMENT OF ECONOMIC INSULATION THICKNESS ANALYSES	46
4.3.1	Traditional Analysis of Economic Thickness.	46
4.3.2	Cost Savings from Insulation Capital Investment	47
4.3.3	Discounted Cash-Flow Investment Analysis.	49
4.4	COMPUTER ANALYSIS PROGRAMS	50
4.5	SURVEY OF ECONOMIC CRITERIA OF INDUSTRIAL USERS.	52
4.6	OBSERVATIONS AND CONCLUSIONS	53
4.7	REFERENCES	54
5.	ASSESSMENT OF HEAT TRANSMISSION INFORMATION FOR THERMAL INSULATIONS	55
5.1	INTRODUCTION	55
5.2	ASSESSMENT OF ASTM ACTIVITIES.	57
5.3	ASSESSMENT OF INSULATION INFORMATION	60
5.4	OBSERVATIONS FROM MEASURERS	69
5.5	REFERENCES	75
APPENDIX A.	INDUSTRIAL ORGANIZATIONS CONTACTED	79
APPENDIX B.	ASTM — SPONSORED SYMPOSIA	85
APPENDIX C.	ASTM TEST METHODS	93
APPENDIX D.	ASTM THERMAL CONDUCTIVITY EQUIPMENT AND STANDARDS SURVEY	111
APPENDIX E.	OTHER METHODS TO MEASURE HEAT TRANSPORT	137
APPENDIX F.	EFFECTS AND MECHANISMS IN HEAT TRANSMISSION.	159

LIST OF FIGURES

- Fig. 4.1. Economic Thickness of Insulation. Provided by Thermal Insulation Manufacturers Association and reproduced by permission.
- Fig. 5.1. Range of Thermal Conductivities of Low-Conductivity Materials at or Near Room-Temperature. Reproduced from Pratt¹ by permission of Academic Press.
- Fig. 5.2. Relationships Between Thermal Conductivity and Temperature for Typical Thermal Insulations and Other Low-Conductivity Materials. Reproduced from Pratt¹ by permission of Academic Press.
- Fig. 5.3. Apparent Thermal Conductivity Versus Temperature for Various Materials in Air at 1 atm (0.1 MPa). Reproduced from Glaser et al.¹⁴
- Fig. 5.4. Thermal Conductivities and Sample Densities According to the ASTM Specifications.³
- Fig. C-1. Schematic Drawing of the Guarded Hot Plate Method. From *Thermophysical Properties of Thermal Insulating Materials*, ASD-TDR-62-25 (July 1962).
- Fig. C-2. Histogram of Percentage Departures of Individual Conductivity Measurements of Laboratories from those of the Reference Laboratory on the Same Specimens in the 1951 Round Robin. From Robinson and Watson;² reproduced by permission of American Society for Testing and Materials.
- Fig. C-3. Schematic Drawing of Heat Flow Meter Apparatus. Left: single-meter type. Right: double-meter type. Reproduced from 1974 *Book of ASTM Standards* by permission of the American Society for Testing and Materials.
- Fig. C-4. Guarded Hot Box Method Showing the General Arrangement (a), and Two Alternate Assemblies (b and c). Reproduced from Pratt⁴ by permission of Academic Press.
- Fig. C-5. Guarded-End Pipe Insulation Tester. Reproduced by permission from 1974 *Book of ASTM Standards*.
- Fig. C-6. Cross Section of the ADL Model 12 Flat Plate Calorimeter. Reproduced by permission from the 1974 *Book of ASTM Standards*.
- Fig. C-7. The Guarded Refractory Brick Method. From *Thermophysical Properties of Thermal Insulating Materials*, ASD-TDR-62-215 (July 1962).
- Fig. E-1. Radial Flow Method for Powders and Particulate Materials. A, terminal head for current and voltage leads; B, ceramic support tube; C, upper support heater; D, upper shell heater; E, main shell heater; F, ceramic core; G, specimen; H, ceramic shell; I, shell insulation; J, stainless steel case; K, lower support heater; L, lower shell heater; M, ceramic support

rod; N, removable plug; T, thermocouple. From A. W. Pratt, Chap. 6 in *Thermal Conductivity*, Vol. 1, Academic Press, London, 1969. Reproduced by permission of Academic Press.

- Fig. E-2. The Powders Radial Heat Flow Apparatus of Godbee and Ziegler.³
- Fig. E-3. The ORNL Radial Heat Flow Apparatus as Used for Rigid Samples. From Godfrey et al.⁷
- Fig. E-4. Powder Can that Replaces the Sample Disks in the ORNL Radial Heat Flow Apparatus. Lavite bushings insulate the axial core heater from the can. From Godfrey et al.⁵
- Fig. E-5. Radial Flow Thermal Conductivity Calorimeter for Super-Insulations. From A. W. Pratt, Chap. 6 in *Thermal Conductivity*, Vol. 1, Academic Press, London, 1969. Reproduced by permission of Academic Press.
- Fig. E-6. Spherical Thermal Conductivity Methods. (a) Liquid on both sides, (b) core electrically heated. From P. E. Glaser et al., NASA-SP-5027 (1967).
- Fig. E-7. Non-Steady-State Thermal Conductivity Tester. From P. E. Glaser et al., NASA-SP-5027 (1967).
- Fig. E-8. The Comparative or Disk Method. Reproduced from *Thermophysical Properties of Thermal Insulating Materials*, ASD-TDR-62-215 (July 1962).
- Fig. E-9. Thermal Conductivity of TiC by a Comparative Method Using Alumina Standards. Results of Vasilos,¹⁵ Taylor,¹⁶ and Mirkovich.¹⁴ Reproduced from Mirkovich¹⁴ by permission of the American Ceramic Society.
- Fig. E-10. Steam Calorimeter Apparatus for Measuring Thermal Conductivity of Refractories. From Flynn and Didion.¹⁹
- Fig. E-11. Single-Guarded-Cold-Plate Thermal Conductivity Apparatus. Reproduced from P. E. Glaser et al., NASA-SP-5027.
- Fig. E-12. Guarded Hot Box Method for Heat Transfer Through Panels at Low Temperatures. Reproduced from Hickman²¹ by permission of Academic Press.
- Fig. E-13. A Double Hot Box Apparatus. 1. Fans - 2. Refrigerating coils - 3. Electrical resistances - 4. Light-reflecting screens - 5. Heat insulation - 6. Air partition - 7. Wall specimens. From Codegne and Ferro.²²
- Fig. E-14. Schematic Arrangement for Line Source dc Heating Method. B, constant-voltage dc source; H, line source; A, milliammeter; P₁, potentiometer; P₂, preamplifier; RE, recorder; R₁, R₂, R₃, resistors; S, switch (SPST); T₁, T₂, thermocouples; TC, reference junction. Reproduced from Underwood and McTaggart²³ by permission of Academic Press.

- Fig. E-15. Schematic Diagram of Thermal Conductivity Probe. Reproduced from Pratt¹³ by permission of Academic Press.
- Fig. E-16. Schematic Drawing of the ORNL Plane Probe.³⁰
- Fig. F-1. Thermal Conductivity of Crystalline and Amorphous Electrical Insulators as a Function of Temperature. From Powell et al.²
- Fig. F-2. Thermal Conductivity Values of Various Pure Metals as a Function of Temperature. From Powell et al.²
- Fig. F-3. Thermal Conductivity of Various Gases at 1 atm (0.1 MPa) as a Function of Temperature.
- Fig. F-4. "Apparent" Thermal Conductivity of Various Materials at Different Densities. A, kapok; B, bagasse; C, corkboard; D, slag wool; E, mineral wool. Reproduced from Pratt⁴ by permission of Academic Press.
- Fig. F-5. Thermal Conductivity Versus Air Pressure for 74 kg/m³ Type A Insulation at 65°C Mean Temperature. —, Experimental; ---, theoretical (theoretical curve neglects contribution by air convection). Reproduced from Pratt⁴ by permission of Academic Press.
- Fig. F-6. Loss by Convection Versus Density of Fiber Glass. Reproduced from Pratt⁴ by permission of Academic Press.
- Fig. F-7. Thermal Conductivity Versus Air Pressure for Three Densities of Type A Insulation at 338 K Mean Temperature; —, Experimental; ---, Theoretical. Reproduced from Pratt⁴ by permission of Academic Press.
- Fig. F-8. Contribution by Each of Mechanisms of Heat Transfer in Type A Insulation at Atmospheric Pressure Versus Insulation Density at 338 K Mean Temperature. Reproduced from Pratt⁴ by permission of Academic Press.
- Fig. F-9. Relation Among Permeability, Density, Thermal Conductivity, and Fineness Index. (a) Air-flow permeability K_l versus mass/volume ρ for four families of glass fiber materials of four different fineness indices. (b) Thermal conductivity λ^* measured for some glass fiber insulating materials versus mass volume. Iso-fineness mean curves. Reproduced from Fournier and Klausfeld¹¹ by permission of American Society for Testing and Materials.
- Fig. F-10. Thermal Conductivity λ^* Versus Mean Temperature for Glass Fiber Materials. Fineness index 3.8 (5g). Five values are considered for mass/volume. Reproduced from Fournier and Klausfeld¹¹ by permission of the American Society for Testing and Materials.
- Fig. F-11. Thermal Conductivity of Various Thermal Insulations as a Function of Temperature. (a) Glass and rock fibers of various densities. (b) Fibrous and other materials of higher density. Copied from Ferro and Sacchi¹⁸ by permission of Plenum Press.

- Fig. F-12. Gas Pressure, Temperature, and Bulk Density Relationships for a High Temperature Fibrous Insulation. From Pettyjohn.²¹ (a) Density = 55 kg/m³. (b) Density = 98 kg/m³. (c) Density = 149 kg/m³. (d) Mean temperature = 780 K.
- Fig. F-13. Thermal Conductivity of Rigid Fibrous Carbon Insulation as a Function of Temperature Showing the Effect of Graphite Flake Additions on Radiative and Conductive Heat Transmission. From Rainhart et al.²²
- Fig. F-14. Thermal Conductivity as a Function of Time for Urethane Foam. T_A is a short induction period. At T_B , air in the foam has reached atmospheric pressure, diluting the Freon gas. At T_C , all condensed Freon has vaporized. At T_D , all Freon has diffused out of the foam. Reproduced from Ball et al.²³ by permission of Pergamon Press.
- Fig. F-15. Thermal Conductivity of Two-Phase Mixtures Calculated under the Following Assumptions: 1, Minimum Conductivity; 2, Maximum Conductivity; 3, Phase 2 Continuous; 4, Phase 1 Continuous; 5, Random Mixture. Reproduced from Pratt⁴ by permission of Academic Press.
- Fig. F-16. Effect of Number of Radiation Shields on Net Heat Flux. [Radiation shields: crinkled aluminum polyester film. Spacers: 1/8- by 1/8-in. (3 by 3 mm) mesh vinyl-coated fiber glass screen.] From Glaser et al.³²
- Fig. F-17. Moisture in Ottawa Sand. (a) Equilibrium moisture distribution: initial 2% and 4%-moist Ottawa sand; 160 kg/m³ dry density; mean temperature, 297 K; average temperature gradient 330 K/m, determined by hot plate apparatus. (b) Conductivities of Ottawa sand determined by guarded hot plate apparatus; mean temperature, 297 K; temperature gradient 330 K/m. Reproduced from Pratt⁴ by permission of Academic Press.
- Fig. F-18. Equivalent Conductivity, λ^* , of Porous Material (Conduction and Diffusion). Reproduced from Pratt⁴ by permission of Academic Press.
- Fig. F-19. The Dependence of the Thermal Conductivity of Soft Fiber Board on Relative Humidity. Samples II and III adjacent to hot plate, I and IV adjacent to cold plate. Reproduced from Madsen⁴⁰ by permission of Pergamon Press.
- Fig. F-20. Vapor Permeability of Expanded Cork with Asphaltic Binder and of Expanded Polystyrene Versus Density at 100% Humidity on One Side and 50% on the Other and $t_1 = t_2 = 20^\circ\text{C}$. Reproduced from Ferro and Sacchi⁴¹ by permission of Pergamon Press.
- Fig. F-21. Vapor Permeability μ^* of Expanded Phenolic Resin (Density 56.3 kg/m³) Versus Mean Temperature $t_m = (t_1 + t_2)/2$ at Different Values of Temperature Gradient dT/dx but at Constant Vapor Pressure Difference $p_1 - p_2 = 12.9$ mbar (1.29 kPa). Reproduced from Ferro and Sacchi⁴¹ by permission of Pergamon Press.

LIST OF TABLES

- Table 1.1. Categories of Industry Providing Assessment Input
- Table 3.1. Industrial Insulations by Temperature Range of Application
- Table 3.2. Selected Properties of Thermal Insulations Often Used in Design
- Table 3.3. Energy Consumption of Selected Industries
- Table 3.4. Estimated Heat Rejection in the Six Biggest Fuel Consuming Industries (1972-1973)
- Table 3.5. Estimated Energy Conservation Potential in Immediate Period in Six Largest Energy-Consuming Industries
- Table 3.6. Estimated Immediate-Term Energy Conservation Potential in Energy-Intensive Industries by Use of Increased Insulation and Maintenance of Steam Distribution Systems
- Table 5.1. ASTM Thermal Methods and Committee Responsibilities
- Table 5.2. Example of Published Information on Thermal Conductivity of Insulation Materials. Reproduced from *ASHRAE Handbook of Fundamentals*,⁴ by permission of the American Society of Heating, Refrigeration, and Air-Conditioning Engineers, Inc.
- Table C-1. Minimum Linear Surface Dimensions of Guarded Hot Plate
- Table F-1. Thermal Conductivity of Type A Fiber Insulation with Different Gases at a Mean Temperature of 338 K and for a Temperature Gradient of 26 K/cm
- Table F-2. Factors to Use for Moisture Content

**THIS PAGE
WAS INTENTIONALLY
LEFT BLANK**

SUMMARY

Industrial thermal insulation technology was assessed by obtaining input from a variety of sources including insulation manufacturers, system designers, installers, users, consultants, measurement laboratories, open literature, and in-house knowledge. The assessment identified a number of factors relevant to insulation materials and usage that could contribute significantly to improved energy conservation.

A large variety of thermal insulation materials is manufactured for application in various temperature ranges and environments. Additional and improved thermal insulation for steam systems is a key area with immediate energy conservation potential in several of the larger energy-consuming industries. There is presently considerable uncertainty from the thermal insulation user viewpoint as to the accuracy and reproducibility of the available property values of industrial thermal insulations and the stability of these properties under service conditions. Environmental barrier systems required for low- and medium-temperature insulation systems are generally inadequate to fulfill the design life assumed. The result of these uncertainties is that insulation system design is much less precise than required for effective project cost-benefit analyses and most effective energy conservation.

Economic considerations of industrial thermal insulation use include background factors, analysis methods for determining economic thickness, and results from industrial insulation users regarding economic constraints currently affecting their investment decisions. Background factors of importance are present fuel costs and projected fuel cost increases, fuel availability in the case of natural gas, and energy conservation goals. Traditional economic analyses published by the Thermal Insulation Manufacturers Association are not used by many companies, although the traditional design methodology is still considered valid. Shortages and cost of investment capital deter some companies from increasing insulation thicknesses, although thermal insulation is presently recognized for its relatively high return on investment.

The assessment of heat transmission information for industrial thermal insulations examined the role of the ASTM, its recommended standards and specifications, the test methods used for the determination of the thermal conductivity of insulations, the test equipment that is available or used, the property information that is available from all sources, and the gaps in it, the mechanisms of heat transmission in various insulations, and some of the factors that affect the performance of insulations. Each of these areas is discussed in detail, and judgments are made with regard to impact and value. In general, we find room for improvement in each area, particularly concerning product variability and thermal insulation in-service experience. A significant shortcoming is the lack of a systems approach throughout most of industry. Related to this is the ever decreasing amount of information available to the user and system designer as the product moves from laboratory measurements to subassembly testing to in-field system measurements and evaluations.

Immediate industrial energy conservation potential due to increased insulation and improved maintenance is estimated to be of the order of 5 to 10% of the present industrial process energy consumption. This savings represents about $1.2\text{--}2.4 \times 10^{15}$ Btu/year ($1.28\text{--}2.6 \times 10^{18}$ J) in the 1974–1975 time period.

Important recommendations for further work include:

1. An experimental program is needed to measure heat transfer in realistic service situations for insulation systems in all temperature regimes (low, intermediate, and high). The results of such a program would assist designers in material choices, supply necessary parameters for economic analyses, and verify installation practices.

2. An experimental program is needed to obtain reliable and representative energy transport data on currently used insulations. This program should develop realistic test methods and materials, evaluate variations in insulations, obtain a better understanding of the mechanisms of heat transport, and critically evaluate insulation property data.

3. Specific programs should be initiated with directed goals to

- develop improved vapor barrier systems,
- develop more realistic burning rate tests for organic-based insulations,
- improve or replace calcium silicate insulation,
- develop a sterilizable steam system insulation for food processing,
- determine the high-temperature properties of refractory batt insulations,
- educate users, designers, and installers on effective use of insulation.

4. A policy is needed to accelerate insulation investment by industry.

1. INTRODUCTION

About 39% of the total energy usage in this country is associated with industrial processes. In many of these processes, the use of thermal insulation to limit undesirable heat flow is an important factor in determining the technical and economic success of a process. The use of thermal insulation has contributed some and could contribute more to energy conservation.

As a part of their efforts to determine the extent to which thermal insulations are being, or could be, effectively applied, the Energy Research and Development Administration commissioned a study at the Oak Ridge National Laboratory (ORNL) to technically assess existing thermal insulation materials for industrial applications. The specific objectives of this study were to (1) identify what materials are being used and how, (2) determine their suitability in relation to their use, (3) assess the quality, validity, and adequacy of available design and use data, and (4) identify the significant economic factors affecting the usage of insulation.

The assessment was conducted over a period of four months from September to December 1975. Because of the limited time for the study, major emphasis was placed on obtaining information on materials and applications of significance. A wide variety of industries and applications was considered in an effort to obtain an overall view of thermal insulation technology. Both the timing of the study and the wide variety of materials available for this application necessitated a qualitative assessment based only in part on quantitative information. Economic aspects, although recognized as crucial in determining thermal insulation usage, were not within the primary scope of this study and therefore were considered only superficially.

The assessment team organized at ORNL was composed of members of the Metals and Ceramics Division and the Energy Division. Areas of technical expertise represented include physical property measurement, and chemical, metallurgical, and ceramic technology. The sources of information included insulation manufacturers, system designers, installers, users,

independent consultants, and property measurement laboratories, supplemented with material property data from the open literature and in-house knowledge. In an effort to provide an up-to-date state-of-the-art picture, personal or telephone contact with responsible members of each organization was emphasized. A summary of the industries providing input to this assessment is presented in Table 1.1. The number of individual organizations contacted exceeded 100, and they are identified by category in Appendix A.

In order to make the body of the report briefer, much information supportive to Chap. 5 is included in the appendices. This was done to encourage those interested in the general subject of insulation to read all chapters. The authors feel that only in this way can the reader gain a full appreciation for the important interaction of the different aspects covered in each chapter.

Throughout the report the terms "immediate," "near-term," "mid-term," and "long-term" are used repeatedly with respect to energy conservation goals. The meaning of these terms as used here is as follows:

immediate	by year 1980
near-term	by year 1985
mid-term	by year 2000
long-term	beyond 2000.

Table 1.1. Categories of Industry
Providing Assessment Input

Category	Number Contacted
Insulation manufacturers	
Individual companies	32
Manufacturer's associations	3
System designers	
Architect-engineers	6
Consultants	3
Insulation users	
Electric power utilities	6
Steel	4
Nonferrous metals	3
Petroleum refining	9
Industrial chemicals and plastics	5
Paper	3
Equipment manufacturers	3
Cryogenic gases	4
Measurement Laboratories	17
Others	6

2. CONCLUSIONS AND RECOMMENDATIONS

2.1 CONCLUSIONS

The following conclusions were reached as a result of this work. These conclusions represent the sum input from insulation interests including insulation manufacturers, system designers, installers, users, consultants, measurement laboratories, open literature, and in-house knowledge. The individual conclusions are grouped by the topics treated in the text: Assessment of Available Industrial Thermal Insulation Materials, Assessment of Economic Considerations, and Assessment of Heat Transmission Information.

2.1.1 Assessment of Available Industrial Thermal Insulation Materials

1. The quantitative performance of low-, ambient-, medium-, and high-temperature thermal insulation systems is not adequately known as a function of the materials used, the design parameters, the installation practices, or the age of the system.
2. Thermal and mechanical properties of insulation materials such as calcium silicate are deficient.
3. The combustion risks associated with organic foam insulations have not been completely evaluated.
4. The thermal transport properties of inorganic fiber insulations currently on the market are not well understood or optimized for performance.
5. Certification of thermal insulation installers has not been extensively used as a means of standardizing installation practices.
6. The insulation manufacturing industry currently feels that its products are either totally suitable for current needs or that it has new products developed that will satisfy most needs when market conditions develop sufficiently.
7. New total insulation system performance testing techniques such as infrared scanners have not been extensively evaluated, developed, and utilized.
8. Contacts in the steel industry felt that more attention should be concentrated on stack gas heat recuperators as well as on thermal insulations.

9. Verification testing of the properties of available industrial thermal insulations would be very helpful to users and designers. ASTM recommended standards and specifications were not considered adequate by many of our contacts.

10. The types of contracts used to employ architectural engineering firms and the minimum capital cost incentives imposed by industrial customers of A-E firms tend to develop plant and system designs that are not optimized for minimum heat losses via use of thermal insulations.

11. Easily sterilized reflective types of thermal insulation have not been considered for possible use in the food industry.

12. Immediate industrial energy conservation potential due to increased insulation and improved maintenance is estimated to be of the order of 5 to 10% of the present industrial process energy consumption.

2.1.2 Assessment of Economic Considerations

1. The availability of capital at reasonable costs has restricted the increased use of insulation and other process improvements that would otherwise be implemented on a desirable "return-on-investment" basis.

2. There is a wide diversity in the economic criteria used by different industries to choose between capital expenditures such as for thermal insulation. In some cases, payback period is still the controlling criterion used, as opposed to the discounted cash-flow method.

3. Many large industrial companies that use computer analysis for investment decisions have devised their own economic analysis programs for thermal insulation instead of using the ECON-I and R-ECON methods developed by the Thermal Insulation Manufacturer's Association. ECON-I and R-ECON are limited in use because of limited flexibility in several variables that are important to industry - interest rates for capital, insulation costs, and fuel escalation rates.

4. Thermal insulation, when evaluated on a discounted-cash-flow basis, is a good investment even with discounted rates of return of 30 to 50%/year required by some companies for new capital expenditures.

5. Realistic values for service life and thermal properties should be used in economic analysis of specific insulation systems. Optimistic values can distort the cost and fuel savings expected from real performance of insulation systems.

2.1.3 Assessment of Heat Transmission Information

1. Advances in insulation technology are being limited by the lack of open-literature publications and information feedback in three interrelated (but now isolated) areas: materials development, subassembly testing, and in-field evaluation.

2. ASTM activities have been invaluable and vital to insulation technology and have resulted in: a degree of uniformity in prescriptions for testing insulations, four symposia on insulations, and a survey of equipment for measuring thermal conductivity.

3. Thermal conductivity or conductance tests on insulations are difficult to perform and consequently they are often expensive, are fraught with incipient errors, and yield questionable results. Acceptable materials for thermal conductivity standards are virtually nonexistent.

4. Most of the available apparatuses, which are based on ASTM test method prescriptions, are useful for tests on product thicknesses that are much less than are actually used in installations. Current practice is to extrapolate thin sample results to thick sample applications, although justification of this extrapolation may not be valid.

5. The ASTM maintains test prescriptions on at least seven methods of measuring heat transmission. Numerous other methods have been developed to study heat conduction in insulation. Proper use of all techniques requires close attention to experimental detail to obtain valid results. Often this close attention is missing, so the results are questionable. There is no panacea for this problem. Few of the scattered published works provide data comparisons with other work, and often the claimed checks on accuracy, reproducibility, and repeatability are inadequate and optimistic. There appears to be no adequate enforcement of policies to remove this difficulty, and this void produces the "least common denominator" approach, which denies any significant advance in methodology on these complex materials.

6. There appears to be no complete single source of valid heat transmission data on thermal insulations. For instance, data are not available on thermal insulation product variability, which may reach 25%, even though this is crucial to the performance and design of many installations.

7. The heat flow through insulation has been identified as dependent on the contribution and interaction of four basic mechanisms: solid conduction, gas conduction in voids, convective transfer in and through voids, and radiation transfer through voids and components of insulation. Studies directed at obtaining a better understanding of the roles of these mechanisms have often led to improved products and installations by identifying and controlling certain material characteristics. Such studies have been conducted on the various generic insulation types including fibrous, cellular, granular, bulk, and evacuated insulations.

8. Relatively few studies have been conducted on in-service variables and their influence on heat transmission in insulations. The effect of moisture in insulations is known to be quite detrimental. However, because the ASTM guides call for tests in dry conditions, definitive studies on moisture effects are not being undertaken.

9. Numerous comments and observations from those involved in heat transmission in the thermal insulations field indicated a spectrum of views. Misapplication of ASTM methods, scrapped equipment, unused facilities, outmoded facilities, lack of reference materials, undefined specifications, limited system testers, few practical studies, and lack of turn-key systems are some of the key phrases used to describe the current arena of thermal insulations.

2.2 RECOMMENDATIONS ON MATERIALS AND APPLICATION

The following recommendations are offered on the basis of our observations and conclusions discussed in this report. We recognize that because of the accelerated nature of this assessment, there are probably important areas that we have failed to address, but it is clear from our contacts with insulation users and thermal insulation system designers that the following address areas of legitimate concern and need at the present time. The recommendations are identified with a usage temperature range.

2.2.1 Low Temperatures

1. Vapor barrier systems for use with insulations must be improved if insulations having any significant water vapor permeability are to be used effectively.

2. More realistic burn-rate tests for organic foam insulations should be devised and put into practice.

3. More realistic vapor permeability tests should be devised and employed for standard characterization of low-temperature thermal insulation.

4. An experimental program should be initiated to measure heat transfer (conductive and radiative) in actual or realistic mock-up service situations for foamed and fiber insulations typically used in this temperature regime. The measurements should include variables of cold-face temperature, temperature difference across the insulation, and functional age of the insulation. Results should be available for use by designers to make realistic material choices for use in this temperature range.

2.2.2 Intermediate Temperatures

1. An improved rigid calcium silicate insulation is needed, having better compressive strength and resistance to fracturing and dusting due to vibration. These improvements should be accomplished with no increase in the effective thermal conductivity if possible.

2. An experimental program should be initiated to measure heat transfer (conductive and radiative) in actual or realistic mock-up service situations for insulations typically used in this temperature regime. These measurements should include variables of cold-face temperature, temperature difference across the insulation, functional age of the insulation, insulation joint design, and weather barrier jacket design. Results should be available for use by designers for use in making realistic material choices for use in this temperature range.

3. A rigid thermal insulation should be developed having a thermal conductivity significantly lower than calcium silicate but retaining the other required mechanical and chemical properties for steam system applications. This insulation should remain economically competitive.

4. Weather barrier systems available for pipes and tanks should be improved both in their design and installation procedures. Mastics and other sealants used to seal joints in these barrier systems should be improved as to their service lives, water permeability, and repairability.

5. Chemical reactions etc. between various organic liquids and calcium silicate and organic foam pipe and tank insulations should be studied to clearly identify systems that are compatible for use in chemical manufacturing plants.

6. Techniques should be developed for improving the insulation of valves and flanges in steam supply systems as to both thermal losses and economics. This is particularly applicable to the calcium silicate type of insulation.

7. An organized effort should be initiated to educate thermal insulation users and designers on the subtleties and vagaries of thermal insulations and their effective use. This should include the important area of heat tracing of process lines.

8. Effort should be initiated to inform and certify thermal insulation installers.

9. A sterilizable steam system insulation suitable for general use in food processing plants should be developed.

2.2.3 High Temperature Range

1. Skid rail insulations for steel heat-treating furnaces should be improved by having lower thermal conductivity and longer service life. Advantages of these systems should be widely publicized.

2. Insulating fire bricks for lower temperature service at about 870°C (1600°F) should be more readily available. Furnace manufacturers commented that availability of bricks of this type is decreasing, requiring use of higher temperature types with their accompanying higher thermal conductivities.

3. Aluminosilicate, alumina, and zirconia fiber batt insulations should be more extensively characterized as to their thermal transport properties at temperatures up to their maximum use temperatures.

Degradation tendencies in selected environments of the aluminosilicate fiber insulations should be reduced if possible. Anchoring systems for the high-temperature batt insulations should be extensively evaluated and demonstrated.

4. The measurement and verification of the heat transfer properties of high-density insulations for use in this temperature range should be accomplished in actual or mock-up service situations to provide more realistic parameters for design and economic analysis.

2.3 ECONOMIC RECOMMENDATIONS

1. Because of interest in and use of the discounted cash-flow method of analysis for capital expenditures by industry, generalized economic evaluation of optimum insulation thickness should include this method.

2. Energy Research and Development Administration should encourage the utilization of economic analyses for insulation investment and to establish the sensitivity of economic thickness to cost factors. The validity of such analyses should be verified through case studies.

3. Economic incentives to industry should be considered to promote improved and additional insulation use in cases where capital availability is postponing fuel savings. Such incentives could include accelerated tax write-off of investment and guaranteed low-interest loans for insulation investments.

2.4 RECOMMENDATIONS ON PROPERTY DETERMINATIONS

1. A strong need exists for the development of realistic test methods and procedures at ambient temperature and as a function of temperature that are applicable to each type of thermal insulation. The ASTM test methods are a step in the right direction but are subject to misapplication and misinterpretation, and should be strengthened.

2. Well-characterized samples of various types of insulations — such as felt or fiber, rigid board, loose fill, pipe, high-temperature foams, and multifoil — should be established as standard test materials so that measurement methods, procedures, and operators can be properly qualified and compared.

3. In-field testing of insulation systems should be encouraged as a means of verifying the design values and assessing insulation and installation variables.

4. Producers of insulations should provide more information about their materials properties, especially their variability, as well as the effects of other variables such as temperature, density, moisture, and aging. An improved understanding of the mechanisms of heat transport in insulations is needed.

5. The ASTM C-16 committee should attempt to overcome the tendency toward the "lowest common denominator" approach to materials specifications and test procedures.

6. A concerted effort should be directed toward the collection, collation, and rationalization of data on thermal insulations from all sources. While much data is available on insulations, it is diffuse, and a significant portion is outdated since the products are being changed constantly.

3. ASSESSMENT OF AVAILABLE INDUSTRIAL THERMAL INSULATION MATERIALS

3.1 ASSESSMENT AND DISCUSSION OF AVAILABLE INSULATION MATERIALS

To permit a useful technological assessment of industrial thermal insulation materials, they are conveniently classified on some logical basis related to their use. The basis chosen for this assessment is the temperature, since the applicability of any given insulation material is typically limited by an upper temperature at which it becomes structurally unstable or noncompetitive because of heat transport through it (relatively high thermal conductivity). An indication of the many types available is shown in Table 3.1. Most thermal insulation materials also have a lower temperature limit of applicability due to undesirable properties. Several properties of thermal insulations are important in addition to the thermal conductivity. Often, some of these other properties will dictate the choice of material rather than the heat transport characteristics alone. A number of these properties are identified in Table 3.2. Standard methods for determining several of these properties are not available, and one must therefore be cautious in comparing a specific property of various insulations and using this as the only basis for materials choice in a given system design. The values of many of these properties for various types of commercially available insulations are unknown. For convenience, in this assessment the temperature scale will be divided into segments related to the range of use of several commercially significant thermal insulations. These temperature ranges are (1) cryogenic, -270°C (-454°F) $\leq T \leq -100^{\circ}\text{C}$ (-148°F); (2) low temperature, -100°C (-148°F) $\leq T \leq 100^{\circ}\text{C}$ (212°F); (3) intermediate temperature, 100°C (212°F) $\leq T \leq 500^{\circ}\text{C}$ (932°F); and (4) high temperature, $T > 500^{\circ}\text{C}$ (932°F).

3.1.1 Cryogenic Range [-270°C (-454°F) $\leq T \leq -100^{\circ}\text{C}$ (-148°F)]

Thermal insulations for use in the cryogenic range consist of both vacuum types and so-called massive insulation, in which one or more solid phases are distributed along with a gas, often dry air, to produce an acceptably low thermal conductivity. Vacuum cryogenic thermal insulation

Table 3.1. Industrial Insulations by Temperature Range of Application

Cryogenic and Low Temperature $[-270^{\circ}\text{C} (-454^{\circ}\text{F}) \leq T \leq 100^{\circ}\text{C} (212^{\circ}\text{F})]$

- Evacuated

- Multifoil
 - Opacified powders

- Mass type

- Glass foams
 - Organic foams
 - Fiber glass
 - Loose fill
 - Balsa wood

Intermediate Temperature $[100^{\circ}\text{C} (212^{\circ}\text{F}) \leq T \leq 500^{\circ}\text{C} (932^{\circ}\text{F})]$

- All inorganic

- Perlite
 - Calcium silicate
 - Foam glass
 - Mineral wool
 - Reflective
 - Loose fill
 - Insulating firebrick

High Temperature $[T > 500^{\circ}\text{C} (932^{\circ}\text{F})]$

- All inorganic, carbon, or metallic

- Loose fill
 - Reflective
 - Insulating firebrick
 - Ceramic foams
 - Ceramic fiber
 - Pyrolytic carbon
 - Carbon fibers

Table 3.2. Selected Properties of Thermal Insulations Often Used in Design

Property	Insulation Type							
	Rigid and Semi-Rigid	Flexible	Blanket, Felt, or Batt	Loose Fill	Reflective	Cryogenic	Insulating Fire Brick	Sprayed and Foamed in Place
Thermal conductivity	X	X	X	X			X	X
Thermal diffusivity	X	X	X	X			X	X
Maximum temperature limits	X	X	X	X	X	X	X	X
Density	X	X	X	X	X	X	X	X
Abrasion resistance	X	X					X	X
Alkalinity	X	X	X	X	X		X	X
Capillarity	X	X	X					X
Flame spread index	X	X	X	X				X
Smoke density index	X	X	X	X				X
Combustibility	X	X	X	X				X
Compressive strength	X	X	X			X	X	X
Hydroscopicity	X	X	X	X			X	X
Linear shrinkage at maximum temperature	X	X	X				X	X
Specific heat	X	X	X	X	X	X	X	X
Tensile strength	X	X	X				X	
Water absorption during submersion	X	X		X				X
Water vapor transmission	X	X						X
Heat transmission					X	X	X	X

systems typically consist of highly polished metal supporting walls with a vacuum space between them. Within this vacuum space there may be multiple metal reflective foils or various inorganic or organic materials coated with metals (so-called opacified powders) depending upon usage temperature. These insulations as applied to industrial systems are typically custom-designed and installed by the insulation vendors.

Performance of these systems after installation is typically guaranteed by the insulation designer or vendor. Manufacture and improvement of vacuum types of cryogenic insulation are highly sophisticated and very specialized. Performance of the present systems in service appears to be reasonably satisfactory from the user's standpoint. The multi-layer evacuated multifoil insulations have typical thermal conductivities in the range of approximately $3 \times 10^{-5} \text{ W m}^{-1} \text{ K}^{-1}$ ($2 \times 10^{-4} \text{ Btu in. hr}^{-1} \text{ ft}^{-2} \text{ }^{\circ}\text{F}^{-1}$) to about $2 \times 10^{-4} \text{ W m}^{-1} \text{ K}^{-1}$ ($0.0014 \text{ Btu in. hr}^{-1} \text{ ft}^{-2} \text{ }^{\circ}\text{F}^{-1}$) and are used in the temperature range from very near 0 K (-459.7°F) up to ambient in some cases.

Other evacuated cryogenic insulations include vacuum spaces containing (1) opacified powders, (2) glass fibers, or (3) uncoated oxide powders. These three types cover a thermal conductivity range of about $1.7 \times 10^{-3} \text{ W m}^{-1} \text{ K}^{-1}$ ($0.0125 \text{ Btu in. hr}^{-1} \text{ ft}^{-2} \text{ }^{\circ}\text{F}^{-1}$) to about $0.08 \text{ W m}^{-1} \text{ K}^{-1}$ ($0.555 \text{ Btu in. hr}^{-1} \text{ ft}^{-2} \text{ }^{\circ}\text{F}^{-1}$), with their thermal conductivities ranking from (1) through (3) in order of increasing conductivity.

Because of the relatively high cost of the evacuated cryogenic insulation system and difficulty of application in some design situations, many types of massive insulations have been examined for use in cryogenic applications. Early materials used for moderately low temperatures included cork and some other natural organic materials. One material, which derived from World War II and which initially showed great promise, was expanded or foamed polyurethane. This material can be foamed into the form of flexible sheets, foamed in place, and foamed into rigid insulation sections. Other foamed thermal insulation materials are polystyrene and rigid foamed glass. Foamed glass is manufactured to

size for piping, etc. or can be shaped during field installation. Foamed urethanes, styrenes, and foam glass owe their relatively low thermal conductivities to their microstructure of closed cells containing air or other gas, which results in greatly reduced heat transfer by gas phase convection and conduction. As we shall see later, these materials differ considerably in resistance to permeation by water vapor and air, with the result that their service lives in cryogenic applications can be quite different. The basic patents for the foamed glass thermal insulation date from 1934 to 1938 in France, and work in the U.S. on this type of material started in 1937.

3.1.2 Low Temperature Range $[-100^{\circ}\text{C} (-148^{\circ}\text{F}) \leq T \leq 100^{\circ}\text{C} (212^{\circ}\text{F})]$

Thermal insulation materials that have been used in this temperature range include some of the evacuated systems discussed previously as well as many nonevacuated foams, powders, and fibers. The thermal conductivities of these systems range typically from $8 \times 10^{-3} \text{ W m}^{-1} \text{ K}^{-1}$ ($0.055 \text{ Btu in. hr}^{-1} \text{ ft}^{-2} \text{ }^{\circ}\text{F}^{-1}$) to $0.1 \text{ W m}^{-1} \text{ K}^{-1}$ ($0.7 \text{ Btu in. hr}^{-1} \text{ ft}^{-2} \text{ }^{\circ}\text{F}^{-1}$). Foamed glass typically has a thermal conductivity of about $0.05 \text{ W m}^{-1} \text{ K}^{-1}$ ($0.35 \text{ Btu in. hr}^{-1} \text{ ft}^{-2} \text{ }^{\circ}\text{F}^{-1}$) at the mid-temperature of this range (32°F), whereas a urethane foam with density of 2 lb/ft^3 (32 kg/m^3) has a reported conductivity value of about $0.02 \text{ W m}^{-1} \text{ K}^{-1}$ ($0.15 \text{ Btu in. hr}^{-1} \text{ ft}^{-2} \text{ }^{\circ}\text{F}^{-1}$). As we shall see later, however, the conductivity value of some insulation materials employed for cryogenic and low-temperature applications increases dramatically in service because of permeation by water vapor, exchange of the low-conductivity gas originally in the cells by air, and possibly by physical deterioration by ultraviolet light. Caution should be exercised in selecting a material for cryogenic or low-temperature insulation applications unless the water vapor permeation properties are well known, documented, and accepted. Foamed polystyrene is another insulation material that has been used for various low-temperature applications. For these applications, it suffers from having relatively high moisture permeability, relatively low mechanical strength, high burning rate, and an absolute maximum service temperature of about 80°C (176°F) due to its softening

temperature of about 90°C (194°F). This low softening point makes the typically required periodic drying of a low-temperature system insulated with foamed polystyrene somewhat delicate. The relative moisture permeabilities of various low-temperature insulations are shown below.¹

Material	Permeability in Perms*
Foam glass	~0
Urethane foam	0.3-6
Polystyrene foam	1-4
Mineral wool	100-200

Foamed plastic insulations are also reported to have a brittle-to-ductile transition at low temperatures. In the temperature range from about -30°C (-22°F) to the upper limit of this range [100°C (212°F)] organic and inorganic massive insulations are used. These include compressed and granulated cork, sandwiched cellular glass and felt board, glass fibers bonded with organic resins, expanded and cellular forms of polystyrene, polyurethane foams, rubber and resin combinations, vinyl chloride cellular foams, wood fibers with suitable binders, polyvinylacetate, cork-filled mastic, expanded vermiculite and perlite, and aluminum foil on paper. Various loose fill forms of some of these insulation materials are also used. Selection of one of these insulations over others is typically dictated by three factors: (1) form (i.e., rigid board vs flexible board vs loose fill) and requirements of the insulation design, (2) price, and (3) availability. Actual trade-off analyses of thermal insulations for use in this temperature range based on accurately known thermal conductivities, moisture permeabilities, and other properties in the service environment are apparently quite rare.

*The perm is defined as the transport of 1 grain of water vapor per square foot of cross section perpendicular to the vapor flux per hour per inch of mercury pressure differential in the direction of the flux.

3.1.3 Intermediate Temperature Range [100°C (212°F) $\leq T \leq 500^{\circ}\text{C}$ (932°F)]

Thermal insulations available for use in this temperature range include inorganic ceramic materials such as glass fibers, rock wool fibers, various bulk and powdered oxides, calcium silicate, bulk glasses, high- and low-density ceramic bricks, and some specialty reflective systems. This temperature range is very important for industrial applications, as it includes temperatures typically encountered in steam systems and most chemical and petrochemical processes. Many of the insulations used in this temperature range have maximum service temperatures above 500°C , and thus discussion of them relevant to this temperature application range should not be interpreted as indicating maximum use temperature unless this is referred to specifically in the text.

An important type of insulation that is used extensively in this temperature range is that based on fiber-bonded hydrous calcium silicates. Until recently, asbestos fibers were used extensively to provide calcium silicate insulation with reasonable mechanical strength for use on piping etc. Glass fibers are now generally employed for this purpose because of health hazards associated with asbestos. Other insulation types used in this range include: (1) diatomaceous silica, (2) cellular glass to about 450°C , (3) glass fiber bonded with high-temperature binders, (4) magnesium carbonate with asbestos or other fibers and binders to about 300°C , (5) rock wool or mineral-derived fibers, (6) expanded perlite with binders, (7) ceramic fibers based on the $\text{Al}_2\text{O}_3\text{-SiO}_2$ system (aluminosilicate fibers), silica fibers, Al_2O_3 fibers, and ZrO_2 fibers and vermiculite, and (8) metal sheet reflective systems.

The lowest reported thermal conductivities for materials in this group at the midrange (250°C or about 500°F) are for fiber-bonded calcium silicate, glass or mineral fiber, $\text{Al}_2\text{O}_3\text{-SiO}_2$ ceramic fibers, diatomaceous silica, and the stainless steel reflective systems. These materials all have similar reported conductivities of about $0.07 \text{ W m}^{-1} \text{ K}^{-1}$ ($0.5 \text{ Btu in. hr}^{-1} \text{ ft}^{-2} \text{ }^{\circ}\text{F}^{-1}$). All the insulation materials mentioned relevant to this temperature range have thermal conductivities that increase almost linearly with temperature over temperature ranges of 200 or 300°C .

The selection of a particular insulation for use in this temperature range is partially dictated by the value of the thermal conductivity, but is often strongly influenced by other factors such as mechanical properties, forms available, and cost of installation. In the case of multiple metal sheet reflective systems, they are the only acceptable insulation type for nuclear reactor systems because of the requirement for rapid identification and isolation of any steam or water system leaks and accessibility for radioactive decontamination if required. Insulations for reactor systems must also be readily demountable to allow periodic inspection of piping, welds, etc.

3.1.4 High Temperature Range [$T > 500^{\circ}\text{C}$ (932°F)]

Thermal insulation materials available for use in this temperature range become limited in number when the temperature exceeds about 650°C (1200°F), and materials availability becomes quite restricted above about 1100°C (2012°F). Insulations for use above 500°C are all inorganic and in some cases initially consist of hydrated phases that dehydrate and shrink at high service temperatures. For service above 500°C eight principal types of thermal insulation are available. They are (1) calcium-silicate-based material primarily for piping systems, (2) mineral fiber, (3) ceramic fibers based on the Al_2O_3 - SiO_2 system, (4) oxide fibers, primarily Al_2O_3 or ZrO_2 , (5) carbon fibers, (6) rigid ceramic insulating brick, (7) castable ceramic insulating refractories, and (8) multiple metal foil systems for vacuum applications. Calcium silicate insulations were discussed in the preceding section. In the case of fibrous insulation applications, a choice between mineral fiber (or rock wool), or carbon and ceramic fibers based on the Al_2O_3 - SiO_2 system is based on maximum use temperature, environment, and economic considerations. Until recently, the highest continuous use temperature for any fibrous insulation exclusive of carbon was about 1260°C (2300°F). This is a typical maximum temperature recommendation for ceramic fibers derived from the clay mineral kaolin with a typical $\text{SiO}_2/\text{Al}_2\text{O}_3$ weight ratio of about 1.13. The purer single-oxide fibers, which have appeared on the market recently, have much higher reported service temperatures, reportedly exhibit much

less dimensional shrinkage near their maximum service temperature than do aluminosilicate fibers, and are more stable in strongly alkaline or acidic environments than aluminosilicate fibers.

Single-oxide refractory fiber insulations are presently based upon either Al_2O_3 or CaO -stabilized ZrO_2 , and they are also more stable in reducing atmospheres at high temperature than are fibers that contain silica either as free SiO_2 or in a silicate. The principal deterrent to the wide application of the single-oxide fibers at present appears to be related to (1) their relative newness, (2) their relatively high cost (about 50% more than an aluminosilicate fiber installation of comparable size), and (3) present concerns about the long-term durability of the refractory anchoring systems required to secure the insulation batts in front (hot side) of the other furnace wall components. These products appear to offer superior performance in those applications requiring their more refractory properties, and it is expected that they will find more widespread use as energy costs continue to increase. It is difficult to specifically compare thermal property values of various fibrous types of insulations, and considerable care must be exercised in doing so because of the different densities of various fibrous products, different resiliencies, and other factors that affect samples used for measurement. Some available thermal conductivity data for Al_2O_3 , ZrO_2 , and aluminosilicate fibers indicate that above 500°C the conductivity increases with temperature with the conductivity vs temperature curve concave upward, as expected when radiation transport and gas phase conduction are significant.

The thermal conductivity values published for the Al_2O_3 fiber material indicate that it has conduction properties similar to aluminosilicate fiber batts up to 1100°C [$k \approx 0.45 \text{ W m}^{-1} \text{ K}^{-1}$ ($3.15 \text{ Btu in. hr}^{-1} \text{ ft}^{-2} \text{ }^\circ\text{F}^{-1}$)], the highest temperature for which conductivity data are available for the more refractory fiber. Similarly, the ZrO_2 fiber material at the same density of about 6 lb/ft^3 (10 kg/m^3) and at 1100°C has a thermal conductivity of about 70% of that of the Al_2O_3 fiber insulation at 1100°C . Thermal conductivity data for these materials to higher temperatures were not available. Maximum use temperatures of

1595°C (2900°F) have been claimed for the ZrO_2 fibers and 1510°C (2750°F) for the Al_2O_3 . No thermal conductivity values were located for these relatively new materials above 1100°C (about 2000°F).

The insulating fiber batt has wide potential application in cyclic furnacing operations or others where the heat capacity of the furnace structure is significant in determining the energy consumption of the process. Use of insulation batting as the front or inner wall of these furnaces greatly reduces the amount of heat input to the furnace required to achieve a given charge temperature. Batts can also lower heat losses in continuous furnaces in that they have a significantly lower conductivity than insulating bricks. The reported thermal conductivity values for Al_2O_3 and ZrO_2 fiber batts with densities of 6 lb/ft³ (10 kg/m³) are significantly lower than those published for the higher temperature grades of insulating firebrick [i.e., for use above 1260°C (2300°F)]. At 1093°C (2000°F), available data show that the Al_2O_3 batt material has a conductivity about 85% of that of the insulating firebrick ordinarily used in this temperature range while the ZrO_2 batt material has a reported conductivity about 45% of that of the insulating firebrick used at its somewhat higher temperature limit.

Ceramic castable and ramming refractories for use to about 1650°C (3000°F) have published thermal conductivity values of 1.2 to about 2.2 W m⁻¹ K⁻¹ (8-15 Btu in. hr⁻¹ ft⁻² °F⁻¹) at 982°C (1800°F). The compositions of these materials are quite variable, and the manufacturers of these products frequently adjust the compositions for particular applications. These materials have much higher conductivities than the previously discussed insulating fiber batt structures or insulating brick and are not very competitive in terms of resistance to heat transfer with the refractory fiber materials or more conventional insulating firebrick. These materials do offer a unique solution to many refractory application problems due to the relative ease of installation and relatively wide range of compositions available. Castables and ramming mixes usually have relatively high porosity and therefore their thermal conductivity in service is a strong function of the ambient gas in the service atmosphere.

Multiple foil or metal sheet reflective insulations for high-temperature use are usually fabricated of refractory metal such as molybdenum or tungsten separated by refractory metal pins or spacers. These units can be used only in vacuum, inert, or reducing atmosphere and are typically employed in electrically heated furnace equipment having refractory metal heating elements. These insulations function as multi-reflective radiation shields and are quite effective for their specialized application at hot-wall temperatures as high as 2500°C (4500°F). Their cost is relatively high, and like the multifoil evacuated insulations for very low-temperature cryogenic applications, they are employed because in their particular application there is essentially no alternative.

Carbon fibers and carbon fiber batts or felt are also effective high-temperature thermal insulations for use in either vacuum or inert-atmosphere environments. These insulations are typically used in furnaces where refractory metal multiple reflecting foil insulation systems are considered too massive, fragile, expensive, or all three. The major considerations concerning use of carbon fiber insulations are the effective carbon pressure at the operating temperature, oxygen pressure in the furnace atmosphere, and potential reactions between the carbon and metal components within the furnace. The equilibrium carbon pressure is relatively high at a given temperature compared with other refractory compounds, and this tendency for carbon evaporation is objectionable in some potential applications of carbon or graphite felt insulations. Carbon fiber insulations having controlled anisotropy have been marketed in the past few years, and these reportedly have superior thermal insulating properties relative to graphite foil and typical graphite felt materials. Thermal conductivity values reported for rigid oriented carbon fiber insulation vary from $0.04 \text{ W m}^{-1} \text{ K}^{-1}$ ($0.3 \text{ Btu in. hr}^{-1} \text{ ft}^{-2} \text{ }^{\circ}\text{F}^{-1}$) at about 540°C (1004°F) to $0.19 \text{ W m}^{-1} \text{ K}^{-1}$ ($1.4 \text{ Btu in. hr}^{-1} \text{ ft}^{-2} \text{ }^{\circ}\text{F}^{-1}$) at about 1430°C (2606°F). The temperature dependence of the conductivity of this material is illustrated in Fig. F-13, Appendix F. At 540°C, the available data show this material to have a conductivity about 40% that of graphite felt at the same temperature. Similarly, it has a

conductivity about an order of magnitude less than that of graphite foil at about 600°C. The variety of carbon-base insulations available makes them attractive for many applications. The foils and felts of carbon are essentially as flexible as those made of glass or oxide fibers. The rigid, oriented type may be obtained over a wide range of compressive strengths with the strongest types showing somewhat higher conductivities because more of the carbonized bonding agent is used. An important, though not generally appreciated, aspect of these carbon products is that they experience irreversible increases in conductivity with time at high temperatures (>2000°C) because of incipient graphitization of the carbon fibers.

3.2 ENERGY CONSERVATION POTENTIAL OF THERMAL INSULATIONS

In this section we shall attempt to analyze various process energy requirements for energy-intensive manufacturing industries to assess the energy saving potential by use of either more of presently available thermal insulations or better than state-of-the-art insulations. In this assessment the most energy-intensive industries were first identified, then those unit operations that have potential for improved energy conservation were pinpointed, and finally those operations where thermal insulation can play a more significant role were identified. Several analyses²⁻⁸ have recently been conducted of selected industries in which the manufacturing energy input and losses associated with the final product are identified. These efforts have been of considerable help in our identification of the future energy conservation potential of various manufacturing industries and identification of areas where thermal insulations are or could be important. The estimated accuracies of the energy figures we could locate were usually no better than ±20%.

The industries that use most energy in the industrial sector are (1) steel, (2) aluminum, (3) chemical, (4) petroleum, (5) paper, (6) stone-clay-glass-cement, and (7) food. The energy consumption of the significant industries in periods for which data could be identified⁸ are given in Table 3.3. These seven industries are estimated to consume about 75% of the total energy requirements of all manufacturing industries in 1975.

Table 3.3. Energy Consumption of Selected Industries

Industry	Energy Consumption ^a		Period
	(J)	(Btu)	
Aluminum	1.5×10^{18}	1.4×10^{15}	1974
Steel	3.6	3.5	1972
Other metals	1.1	1.0	1972
Chemical	4.9	4.6	1973
Petroleum	3.2	3.0	1971
Paper	2.7	2.6	1972
Glass	0.3	0.3	1972
Structural clay products, cement, and others	2.1	2.0	1972
Food	1.4	1.3	1971

^aThese energy values were computed on the basis that electricity, where employed, cost an energy equivalent of 9935 Btu/kWhr for an assumed average electric power plant efficiency of 34%.

The amount of energy rejected as heat in various temperature ranges per year for these manufacturing industries has recently been estimated by Reding and Shepard,⁸ and these will be discussed since some of this rejected heat represents energy potentially conservable through better use of thermal insulations. Some of Reding and Shepard's data are shown in Table 3.4 for the six subject industries.

Analysis of the data in Table 3.4 provides a reasonable estimate of the total rejected energy in the form of heat from each of the major industries in each temperature range. The total rejected heat is approximately 12.0×10^{15} Btu (12.7×10^{15} J), and this represents about 56% of all the energy used by these industries per year in the 1971-1973 period. The grand totals in Table 3.4 indicate the estimated quantities of energy in the form of heat available in the various temperature ranges. These estimates show that a very large fraction (47%)

Table 3.4. Estimated Heat Rejection in the Six Biggest Fuel Consuming Industries (1972-1973)

Industry (or Process) and Operation	Rejected Heat, (10 ¹² Btu/year) ^a					Total, All Ranges
	Radiation, Convection, Conduction, and Unaccounted Losses ^b	Below 100°C	100— 250°C	250— 800°C	800— 1800°C	
<u>Chemical</u>						
Chlorine/caustic soda	40	254	51			
Ethylene/propylene	20	151	79	40		
Ammonia	32	115	139	40		
Ethylbenzene/styrene	1	24	28			
Carbon black	2		32			
Sodium carbonate	2	36	16			
Oxygen/nitrogen	1	171	147			
Cumene		4	4			
Phenol/acetone		8	8			
Other	150	628	290	79		
TOTAL	248	1391	794	159		2,345
<u>Primary Metals</u>						
Steel	298	79	397	596	795	
Aluminum	119	378	79	20	79	
Other	119	397	119	40	79	
TOTAL	536	854	595	656	953	3,058
<u>Petroleum</u>	318	994	497	695		2,186
<u>Paper</u>	199	1391	755	119		2,265
<u>Glass-Cement-Other</u>						
Cement	119	79	40	119		
Glass	99	60	12	87	36	
Other	99	79	40	159	20	
TOTAL	317	218	92	465	56	1,049
<u>Food</u>	60	795	159	119		1,073
GRAND TOTALS	1679	5643	3110	2213	1009	11,975
Ratio to Grand Total Σ		0.47	0.26	0.18	0.09	

^aTo convert to 10^{15} J/year, multiply by 1.0543. The estimated accuracy of the values is $\pm 20\%$.

^bRadiation etc. losses are distributed within other losses shown in the table.

of the rejected heat is available at a temperature less than 100°C. Similarly, about three-fourths of the rejected heat is available at less than 250°C and about 27% of the rejected heat is available in the temperature range 250–1800°C.

The biggest potential for immediate-term energy savings is thus obviously in those manufacturing process operations in which relatively low-quality heat is rejected (i.e., at temperatures below 250°C). This loss is about 8.8×10^{15} Btu/year (9.3×10^{15} J/year). Similarly, there is a significant potential for immediate-term energy savings in manufacturing process operations where the rejected heat is available above 250°C. About 3.2×10^{15} Btu (3.4×10^{18} J) is rejected in this higher temperature range. In terms of crude oil equivalent, 8.8×10^{15} Btu (9.3×10^{18} J/year) represents about 1.5×10^9 barrels, assuming⁹ a barrel of crude oil produces 5.8×10^6 Btu (6.1 GJ). This represents about 58% of present U.S. crude oil imports. Also, 3.2×10^{15} Btu is roughly equivalent to 21% of the present U.S. crude oil imports. Later, we will show that roughly about a third of the total conservable energy in these industries might be conserved via use of more thermal insulation and by use of improved insulation maintenance. Thus, appreciable energy conservation via better thermal insulations and other techniques could have a significant national impact.

Reding and Shepard⁸ have provided an estimate of potential energy savings in the six big fuel-consuming industries on the basis of short-term conservation measures (i.e., less than five years). Research and development on new processes, increasing product yields, new improved thermal insulations, and improved systems may yield additional conservation of energy, but the near-term estimates were made by assuming use of only presently available materials and techniques. The following discussion will include only what is now considered state-of-the-art and thus takes no credit for additional energy conservation that may accrue via research and development results on improved thermal insulations and applications of insulations during the period 1975–1980 or beyond. Reding and Shepard⁸ consider the order of effectiveness of conservation approaches in this immediate-term period to be (1) design modification, (2) insulation and

maintenance, (3) process integration, (4) waste utilization, (5) process modification, (6) operation modification, and (7) market modification.

In this report, we shall focus primarily on item (2) and will review the conservation potential in the six industries. The estimated immediate-term energy conservation potential in the six industries due to increased use of insulation and improved system maintenance is shown in Table 3.5. The estimated energy savings include those expected from steam system improvement plus a reduction of 10% in the fuel required for direct fired processes in each industry by increased use of insulation. The immediate-term conservation potential due to increased insulation and maintenance is obviously substantial, and the ratio of this value to the estimated total immediate-term conservable energy is conservatively of the order of a third of the total. The immediate-term conservable energy by this route is estimated to be about 5 to 10% of the process energy required by the six industries.

Table 3.5. Estimated Energy Conservation Potential in Immediate Period in Six Largest Energy-Consuming Industries

Industry	Estimated Energy Savings by Insulation and Maintenance ^a		Estimated Total Industry Process Energy Usage ^b	
	(Btu/year)	(J/year)	(Btu/year)	(J/year)
Chemical	252×10^{12}	266×10^{15}	2662×10^{12}	2810×10^{15}
Primary metals	500	528	5900	6230
Petroleum	343	362	3044	3210
Paper	208	219	2563	2700
Glass, cement, structural clay products, others	190	201	2000	2110
Food	47	50	1283	1350

^aEstimated precision, $\pm 30\%$.

^bProcess energy only; does not include feedstock energy usage.
Estimated precision, $\pm 10\%$.

Various recommendations for use of increased application of thermal insulation and maintenance in each industry in the immediate-term will now be discussed.

3.2.1 Immediate-Term Conservation Considerations

Increased application of insulation and improved insulation maintenance of steam systems in several of these industries have a significant energy conservation potential. These are indicated in Table 3.6. The estimated⁶ reduction in chemical industry steam usage by this immediate-term fix would be about 20%. In addition to these estimated energy savings shown in Table 3.6, the industries could effect additional savings, indicated by comparing the estimated energy savings values for each industry in Tables 3.5 and 3.6. In the primary metals industries, use of the new oxide fiber insulation batting systems and more extensive use of skid rail insulations in metal heat treating furnaces could save considerable energy. More extensive use of thermal insulation in refineries, steam generators, steam strippers, reactors, flash columns, separators, and fractionators, which are typically poorly insulated, could save additional energy.⁶ The glass-cement-structural-clay-product industries can save additional energy by greater insulation of annealing and tempering furnaces as well as cement kilns.⁷

Table 3.6. Estimated Immediate-Term Energy Conservation Potential in Energy-Intensive Industries by Use of Increased Insulation and Maintenance of Steam Distribution Systems

Industry	Estimated Energy Savings ^a	
	(Btu/year)	(J/year)
Chemical	199×10^{12}	210×10^{15}
Primary metals	120	127
Petroleum	160	170
Paper	200	211
Glass, cement, structural clay products	40	42
Food	40	42

^aEstimated precision, $\pm 30\%$.

3.2.2 Near-Term Conservation Consideration

Longer term (approximately five years; i.e., beyond 1980) energy conservation via use of thermal insulations could be increased in at least three ways. (1) Improved or more effective thermal insulations than those presently available would reduce heat flows for a given insulation thickness. (2) Improving the hot-wall refractories used in the aluminum, steel, and ceramic industries would allow lower effective furnace wall heat transfer, permitting higher inner wall temperatures without an adverse shortening of the life of the dense refractories used in furnaces to contain molten metals and glasses or for densifying ceramics. (3) Castable and plastic mix refractories for use in the steel, aluminum, chemical, and petrochemical industries having higher service temperatures, lower thermal conductivities, and/or improved mechanical properties would allow improved reactor vessel and furnace thermal insulation without significant shortening of the service life of the refractory linings.

It is obvious from the foregoing that the thermal insulation of directly fired process equipment and steam supply systems plays a major role in dictating energy flow in the energy-intensive industries. Improved insulations, more use of insulation, and more economical insulations could have a significant impact. Also, greatly improved insulation-weather barrier systems and installation practices could play a major role in upgrading current steam system performance.

3.3 OBSERVATIONS FROM INSULATION MANUFACTURERS, INSULATION USERS, AND EQUIPMENT AND SYSTEM DESIGNERS

Personal and telephone discussions were held with many organizations and representatives of companies involved with the manufacture and marketing of various types of industrial thermal insulations. The purpose of these contacts was to determine (1) the presently available thermal insulations and their published properties, (2) the viewpoint of the insulation manufacturing industry regarding the needs for industrial thermal insulations in near-term that have significantly improved properties relative to presently available materials, (3) the viewpoint of

industrial insulation users regarding the adequacy of currently available materials to satisfy industrial needs, and (4) the viewpoint of industrial thermal insulation system designers, including architectural-engineering firms, regarding adequacy of currently available materials. The organizations (listed in Appendix A), which represent various groups of thermal insulation manufacturers, were all very cooperative in helping us to establish contact with their members, helping us to obtain published data for presently available insulation products, and providing us with copies of calculational methods that can be used to assist in certain thermal insulation designs. In general, we were not able to thoroughly assess the attitude of specific insulation manufacturing companies toward real needs for improved thermal insulations in the immediate-term. The general industry feeling on this point appeared to be that presently available insulations were quite good and that increased utilization of these materials by their customers will offer the best immediate-term possibility for significant energy conservation. Some of the insulation manufacturers indicated that they actually have better insulations developed, but that market conditions have not warranted their introduction.

Thermal insulation users were equally helpful in providing us with candid opinions and observations regarding the adequacy of currently available insulation materials. Representatives of various large companies in the energy-intensive industries often showed great interest in the objectives of this assessment and usually provided answers to our questions except in the areas centered about the economic parameters they used in thermal insulation systems designs. These parameters were typically considered to be proprietary information.

Numerous conversations with industrial users of thermal insulations helped considerably in bringing into focus the typical situation between the manufacturer, user, and installer of insulation. The relation between the latter two in many installations really determines the final performance of the insulation system. For discussion purposes here, the term "insulation system" refers not only to the thermal insulation material itself, but any support structure required plus any environmental isolation barrier typically used or required with a given type of insulation.

Discussions, primarily by phone, were held with several companies in the industrial groups: chemicals, steel, aluminum, petroleum, paper, cement, plastics, glass, foods, electric utilities, and architectural engineering. In many cases, a given company had a specific person on its staff designated to assist in designing insulation, to actually do the designs, or to check insulation designs before authorization for construction. In several cases, we were fortunate to contact these people, and they were generally very helpful in giving us an insight into the application of thermal insulations from the user's viewpoint.

The following are synopses of the comments and viewpoints that were obtained from each type of industry.

3.3.1 Industrial Chemicals

One of the major insulation requirements is for steam lines, reactor vessels, and reactor piping. Temperature requirements for these applications typically range from ambient to approximately 250°C. Principal requirements of the insulation are (1) the insulation system must be essentially inert regarding flash point depression etc. for relevant organic liquids that may be spilled or leaked onto the insulation, (2) the insulation should have reproducible thermal transport properties (i.e., the properties should not vary significantly from batch to batch, etc.), (3) the insulation and its barrier system should be fairly resistant to mechanical abuse, (4) the barrier system should have a sufficiently low water leakage rate to prevent significant amounts of water from penetrating to the insulation, and (5) the insulation should be relatively easy to install on valves, because present systems for steam valve insulation are about three times as expensive as a similar length of straight pipe run. One large chemical firm contacted is presently insulating every steam valve in its plants in spite of this cost.

One problem cited for this type of insulation, which at present is largely calcium silicate, is low mechanical strength of present non-asbestos-containing calcium silicate insulations leads to breakage, shrinkage, and hot spots. For example, friability of this material now often results in entire boxes of insulation arriving on the construction site in which all the pieces are broken. Another problem area is the

inadequacy of the weather-barrier systems used with this type of insulation. Many users feel that none of the barriers now available are really watertight for the service life of the insulation. Also, installation practices used by installation contractors vary greatly. There is apparently no certification by installation personnel and there is essentially no verification of the thermal performance of a system by the user, installer, or insulation vendor once it is installed. Both certification of personnel and verification of insulation performance were cited as very desirable by many insulation users. A few cases were cited in which process temperatures could not be maintained on a new system and additional heat tracing of lines had to be installed. Several of the larger companies used computer programs to assist in thermal insulation designs. Critical factors in these design programs, discussed in Chap. 4, include constraints imposed by the individual corporation's accounting and financial system as well as specified factors related to current economic conditions in addition to heat transfer constraints. These factors and their values were considered proprietary information by all the companies who told us they used such a system to aid them in their insulation designs. The methods will be discussed in detail in Chap. 4.

Lack of knowledge on effects of currently available pipe insulations on ignition and detonation properties of various organic compounds important in chemical manufacturing was cited as a problem area. Also, there appears to be very little information available concerning degradation or other changes in pipe insulations with time after they are placed into service. Information on good insulation joint design, cements, and mastics is needed. Some companies expressed interest in possibly participating in some future actual field testing and performance verification of piping insulation systems. Instrumentation of present systems for performance monitoring is essentially nil. A new infrared imaging system¹⁰ capable of detecting relatively small temperature and radiation differences on surfaces was mentioned by several companies as a possible way of identifying hot spots, open insulation joints, cracked insulation, etc. This equipment is presently quite expensive and has been evaluated by a few companies. More techniques such as this one or

others will, however, be required in the future for routine monitoring or large systems if energy losses are to really be minimized.

Problems cited relevant to cryogenic systems were clearly separable into two categories. As discussed earlier, for very low-temperature cryogenic systems, the design and installation of these systems are typically contracted out to vendor specialists on a guaranteed performance basis. For intermediate low-temperature service applications, there is considerable discontent with expanded polyurethane because of its tendency to be permeated by water vapor, which subsequently deposits as ice at the cold surface. This progressively destroys the insulation properties of the urethane, although the warmer surface appears normal and dry. The vapor barriers available for low-temperature foamed urethane and polystyrene insulation systems are generally inadequate, and need to be greatly improved, and their performance needs to be verified in service. The toxicity of the vapors from burning urethane and its poor resistance to vertical flame spreading were cited as other reasons for general discontent with the urethane materials.

Foamed glass was cited by several contacts as a superior insulation for use at intermediate low temperatures. Most of these low-temperature systems require a periodic heating and drying because of the inevitable moisture permeation and ice formation. The high-temperature stability of foamed glass relative to urethane or polystyrene foam is another significant advantage for the glass material. Foamed ceramics were mentioned by one supplier as a new material that will be marketed soon as a high-temperature thermal insulation. It may be of some interest for these intermediate low-temperature applications as well. The available conductivity data for a foamed ceramic material at 205°C (400°F) are $0.14 \text{ W m}^{-1} \text{ K}^{-1}$ ($1.0 \text{ Btu in. hr}^{-1} \text{ ft}^{-2} \text{ }^{\circ}\text{F}^{-1}$), compared with $0.087 \text{ W m}^{-1} \text{ K}^{-1}$ ($0.63 \text{ Btu in. hr}^{-1} \text{ ft}^{-2} \text{ }^{\circ}\text{F}^{-1}$) for a foamed glass at the same temperature. The foamed ceramic has a reported density about twice that of foamed glass. The crushing and flexural strengths of this foamed ceramic are very similar to those reported for foamed glass at a density of about 16 lb/ft^3 (260 kg/m^3). This material, with a maximum reported service temperature of 1150°C (2100°F) and low moisture permeation, may have some future applicability to low-temperature systems.

3.3.2 Primary Metals (Steel and Aluminum)

Thermal insulation problems in these industries appear to fall into two categories, (1) those associated with liquid-metal containment furnaces and metal reheat furnaces, and (2) those associated with steam and cryogenic systems. Companies in these industries did not appear quite as energy conscious as our contacts in the chemical industry, although aluminum industry people were quite conscious of their rising electricity costs. Steel companies use relatively large amounts of natural gas and electricity in addition to coal and steam, and their energy awareness has apparently been intensifying rapidly. In discussions concerning improved refractory insulations for use in metal containment furnaces, it was apparent for both steel and aluminum that reducing heat flow through a furnace wall by use of more or improved thermal insulating material on the outside may produce a serious shortening of the furnace hot-wall lining life as a result of this insulation reducing the heat flux through the wall and thereby increasing its temperature. The hot-wall lining life in a furnace is of major importance in steel melting and aluminum reduction and remelting. Improved hot face refractories or changes in furnace design would be required before additional thermal insulation could be used effectively in these areas. Also, representatives of both industries pointed out that a great deal of the thermal losses associated with steel and aluminum are associated with the hot stack gases, and one steel company contact cited the fact that in their facilities, approximately 50% of the sensible heat lost in their processing is in the stack gases. It was felt that more attention should be paid to stack gas recuperation systems in addition to or in preference to thermal insulation. Another steel company contact stated that they are now assuming that energy costs will escalate at 4% per year for the foreseeable future and are factoring this into their thermal designs. Another steel company is in the process of requesting bids on a 16-in.-diam (0.4-m) steam line a mile (1.6 km) long and for the first time are requesting an insulation incremental cost analysis from the vendor.

Shortage of capital was cited as a serious detriment at this time to retro-fit of insulation systems and construction of new systems by

many companies. In most companies insulation projects should provide a return on capital in less than a year due to energy savings, but in many cases even these cannot be presently financed.

Furnaces associated with metal reheating are prime candidates for energy conservation via increased thermal insulation. The new insulating refractory fiber materials discussed previously are of great interest for these applications in the walls of these furnaces in the steel and aluminum industries.

Another example of a steel-heat-treating furnace application that results in considerable energy waste is the reheat furnace design in which steel slabs are conveyed through the furnace on water-cooled skid rails or skids. These rails, which are water-cooled pipes, are initially insulated on all but the top surface upon which the steel slabs rest. There is significant heat loss in the skid rails under this new condition, but historically the rail insulation tends to degrade rapidly with time and furnace heat losses to the rail system increase significantly. Berg¹¹ has estimated that insulation currently available for this application lasts from four months to a year. It is often not repaired or replaced if it deteriorates or is damaged. Berg¹¹ quotes a source who claims that about 50% of the water-cooled skid rails in heat-treating furnaces in the United States are fully insulated, while about 90% of those used in the major steel producing countries abroad are fully insulated. If insulation were applied to the presently uninsulated skid rail systems in the United States, the total saving of fuel would be equivalent to about 30,000 barrels of oil per day or 11×10^6 barrels of oil per year. Another example of the energy savings potential of skid rail insulation systems is provided by Chart and Stock¹² in the following. It has been estimated that 22×10^6 Btu/hr (6.5 MW) will be lost to the cooling water in an average-size steel heat treating furnace with uninsulated rails. The cost of the insulation for a skid rail furnace is a function of the skid pipe size, but for a typical 4-in.-diam (0.1-m) pipe the cost of using insulating tile on the skids is about \$24/ft (79/m) for skid rails, \$45/ft (148/m) for crossovers, and \$19/ft (62/m) for verticals. In an average size furnace there is about 540 ft (165 m) of this water-cooled

pipe, and an installation of this size would cost about \$20,000. Such an installation would save about 2.6×10^8 Btu per year per ft (9 J/m per year) of pipe or about \$112,000/year for the entire 540 ft of pipe, based on a cost of \$0.80/million Btu (0.76/GJ). Thus, such an installation would pay for itself in about two months plus provide longer life to the skid rail pipes. This energy saving is about 1.4×10^{11} Btu/year (1.5×10^{14} J/year) or the equivalent of about 24,000 barrels of crude oil/year/furnace.

3.3.3 Petroleum Industry

Recognition of the economic value of and the corresponding need for effective insulation systems is currently high in the petroleum refining industry. This situation results from the awareness of fuel costs and energy cost trends and also from the application of energy flow analysis in unit operations used in refining plants. Other conditions contributing to the recognition of the value of thermal insulation are the significant cost of insulation systems applicable to petroleum industry applications and the growing awareness of problems and deficiencies in the performance of some insulation systems. One respondent commented that the cost of surface coatings, jackets, and insulation accounted for 4–8% of the capital cost of a new refinery plant currently under construction.

There are several areas where insulation is being upgraded in existing plants. First, insulation thickness is being increased from 1 to 3 in. (25–88 mm) according to one company engineer. Second, insulation is being applied to valves, flanges, heat exchangers, and intermediate temperature storage tanks (fuel oil, waxes, residual oil, boiler feedwater) that have not been insulated in the past. Third, maintenance of insulation, especially protective coatings and jackets, is being stressed as the effects of moisture migration or insulation effectiveness and useful life are being realized. In all these areas, the actions are easily justified on a cost-effective basis.

Another attitude of interest cited in this industry is the preferential treatment of energy-conserving capital investments — improving thermal insulation, for example — compared with capital investments in

general. Several companies required half the rate of return on investment for energy-conserving capital expenditures compared with other capital expenditures. This obviously gives a significant advantage to proposed insulation projects compared with other capital expenditures. Hence, energy-conserving process improvements are being implemented while other possible projects are postponed because of a general shortage of investment capital at the present time.

The large engineering staffs of the petroleum refining companies perform most of their insulation design and material selection; also product evaluation is performed by some companies as an input to material selection. However, there is essentially no verification testing of insulation thermal properties for installed systems; hence, vendor thermal property data for insulation materials are used directly without modification. ASTM standards are not considered adequate for design specifications and are supplemented heavily with company standards.

Insulation effectiveness is generally not verified in service, with a few exceptions in which cursory analyses were performed on newly insulated equipment. Some interest in doing more verification analysis is shown by some of the companies contacted. One contact commented that emissivity of stainless steel and aluminum jackets is higher in practice than indicated in published data.

There were no new basic or functional insulation requirements uncovered by the company survey. However, it identified some problem areas that define requirements for improving the performance of various insulation materials. The major requirements are as follows:

1. improved vibration resistance to breakage for calcium silicate insulations,
2. improved resistance to slumping and compaction for fiber glass and mineral wools,
3. improved moisture-resistant coatings and/or jackets for use in low- and medium-temperature applications.

3.3.4 Paper Industry

The paper industry showed a positive attitude toward the use of thermal insulation. However, the general reaction from the contacts

made in this survey could be characterized on a "business-as-usual" attitude. There is an awareness of increasing fuel prices, but this situation has not triggered much upgrading or economic reevaluation of insulation usage. This situation probably results from the much higher waste heat losses in exhaust gases and steam and water discharges than have been estimated for radiative and convective heat losses. Hence, the investment capital available for energy-conserving process modifications has been applied mostly in the area of waste heat recovery as opposed to thermal insulation.

Insulation system design and material specifications are contracted to architect-engineering (A-E) firms as a part of new plant design. Therefore, our survey disclosed no significant use or criticism of ASTM insulation standards.

There was no indication of in-service verification of insulation installations. Because insulation design is not typically performed by company engineering personnel, there was no significant awareness or interest in thermal conductivity data variability in a given product or between various insulations available for a given temperature range.

There were no new insulation requirements disclosed by the paper companies surveyed.

3.3.5 Architect-Engineering (A-E) Firms

Since these firms provide engineering design and consulting services to the manufacturing and electric utility industries, their main interest and expertise is in thermal and mechanical design of insulation systems as opposed to operational and service-life considerations. These firms typically have two types of contracts. One form of contract is fixed price, which often involves offering a customer a relatively standardized design. The other form of contract is the cost-plus-fixed-fee type. The fixed-price type often tends to result in lower initial capital costs to the customer due to savings incurred in previous design work and construction experience. The cost-plus-fixed-fee type, which would be involved in specific insulation optimization, is typically more costly. One contact cited the observation that many firms prefer to minimize

capital costs of new construction even if it results in future higher maintenance costs during the plant or system life because of tax statutes, etc. This situation tends to cause A-E firms to offer proposals involving minimum capital costs and often involving designs that are not particularly energy conservative. Therefore, the A-E's economic interest would be to minimize the capital cost of insulation systems within the economic design criteria imposed by the plant owner. Operational and maintenance considerations would tend to be secondary to capital cost considerations in design and material selection.

An important design requirement in selected industries is imposed by the OSHA standard that requires steam and hot water lines to be insulated or guarded in situations where personnel contact is possible. The choice of jacket or coating material placed over the insulation is also important in designing the insulation to limit surface temperature. ASTM standards are often used in material specifications to provide a common basis or background for different specifications. However, additional specifications prepared internally are added especially for installation and inspection procedures.

The survey disclosed one situation in which someone attempted to verify the jacket surface temperature calculated by the ASTM-C-680 procedure. A field check showed lower temperatures for these jacket surfaces than were calculated from published thermal data for the materials in the system. No other examples of in-service verification of heat losses or awareness of thermal conductivity data variability were encountered in the survey of A-E firms.

One situation of a new insulation requirement was stated as follows. In nuclear power plants, motion-limiting supports are placed around the primary system piping to confine the discharge flow area of a hypothetical circumferential pipe rupture. The thermal insulation material placed between the pipe and the support needs to be a crushable material to allow for normal differential movement between these elements.

3.3.6 Cement Industry

As indicated earlier, cement manufacture requires significant use of energy in the United States. It requires about 7.2×10^6 Btu to

produce a ton of cement (6.9 MJ to produce a kilogram). Europeans have reduced fuel consumptions to much lower levels than the general case in the United States by using improved techniques of heat transfer in cement kilns. Extensive use of heat recuperators was the principal method by which Europeans have reduced the energy required to produce cement. A large kiln of this type in Europe has demonstrated the capability of producing cement with 3.3×10^6 Btu/ton (3.2 MJ/kg). This is only about 46% of the energy required in the United States. Fluidized-bed processing in cement manufacture also offers some additional gains in fuel efficiency, but this process technique has apparently not been evaluated very extensively in the United States. As much as 20% of cement production costs are often represented by fuel costs, and thus this industry will be relatively sensitive to potential cost savings possible by conserving fuel. Increased usage of thermal insulation in this industry would be primarily in improved kiln linings and steam supply systems.

3.3.7 Glass Industry

The glass industry consists of three major segments. These are (1) glass containers, (2) flat glass, and (3) pressed and blown glass. Because of the nature of the flat glass and the pressed and blown glass segments of the industry, it is very difficult to obtain energy balance data because this information is usually considered to be proprietary. Battelle Columbus Laboratories³ estimates that for 1973 the flat glass segment of the industry used about 67.2×10^{12} Btu (71.0×10^{15} J) and that the glass container industry used 21.6×10^{12} Btu (22.8×10^{15} J).

Most of the flat glass manufacture in the United States has converted to the Pilkington float glass process, in which molten glass leaves the furnace on a bed of molten tin. This process has superior production economics and production capacity compared with the previous flat glass process in which the plate was formed by passing glass in the viscous stage through metal rolls as it left the furnace and was subsequently polished on both sides. This process change has resulted in significant energy savings because of higher production yield. All the furnaces used in glass manufacture except for the glass melting furnace suffer the large stack heat losses common to other industrial furnaces.

The glass melting furnaces are typically large and employ regenerative heat recovery stages, which are often much larger than the furnace tank itself. The result is that large glass melting furnaces may be the most efficient of present large high-temperature industrial furnaces. A possible rival is the basic oxygen steel furnace.

Most comments from contacts in the glass industry regarding energy conservation concerned energy losses from steam systems as well as annealing and tempering furnaces. Some of the new fibrous insulations and more extensive use of recuperators could result in significant energy savings in this industrial sector. Additional thermal insulation of large glass-melting furnaces is not very practical since they make extensive use of recuperators, as mentioned previously, and additional furnace wall insulation would raise the refractory hot-face temperature and result in more rapid degradation of the refractories that contain the molten glass.

3.3.8 Food Industry

Since the food industry requires of the order of 10^{15} Btu/year (10^{18} J/year) it should be examined for the potential of energy conservation. From Table 3.5 the estimated potential energy savings in the food industry is approximately 47×10^{12} Btu/year (50×10^{15} J/year), and almost all of this is heat available at 250°C or less. This energy loss is essentially all from steam lines and food process lines. Very few steam or process lines are insulated in the food industry because of stringent cleanliness requirements. Contacts with large food producers indicated that they typically use bare lines because of the requirement for frequently washing down and sterilizing a facility. They reported that they were not aware of any thermal insulation system that would be impermeable to moisture from frequent washdowns, contribute no particulate matter that might contaminate food, harbor no bacteria, and be flexible under certain piping design requirements.

Usually, no dead-end pipe runs are permitted where food products are involved, and this requires process pipes to be readily disconnected and reconnected to other points in the process stream. Development and demonstration of such an insulation system would be welcomed by the food industry and could result in appreciable energy savings.

3.3.9 Electric Power Utilities

There is a general awareness of the value of thermal insulation in electric power utilities by virtue of the fact that "energy" is their product. However, there is quite a range in the desire to improve thermal insulation performance. Actions taken to decrease heat losses include (1) increasing insulation thickness on valves and flanges and (2) improving fit of insulation sections.

Design procedures vary from subcontracting the entire thermal insulation design based on calculated average heat loss to performing design with in-house engineering personnel. Design of reflective metal insulation for nuclear plants is all subcontracted presently. There is a general feeling that thermal property data are adequate for design, fostered by the subcontracting method of obtaining insulation design. ASTM standards are found to be too general and so are supplemented extensively with company specifications.

Performance verification is not done extensively. Performance is verified in some cases on fossil-fueled plants and on nuclear plants before criticality with system heat balance and heat rate meters. The tests show that hot spots do occur with metallic reflective insulation and calcium silicate insulation at high temperatures.

Insulating odd shapes effectively can be difficult and expensive. The turbine flange was mentioned as one such difficult area to insulate.

3.4 SUMMARY OF TECHNICAL PROBLEMS

Most of the problems identified in this assessment have been mentioned and discussed in previous sections pertaining to specific industries and manufacturing processes. In general the technical problem areas where some near-term energy savings could be accomplished are:

1. improved steam pipe insulations of the calcium silicate or competitive types with lower thermal conductivities and improved fracture and dusting properties relative to present products,
2. greatly improved pipe insulation weather barrier systems to prevent water penetration and degradation of the thermal conductivity,
3. improved and standardized pipe insulation installation practices,

4. cryogenic insulation systems where all pathways of condensible vapors to the cold surface can be closed with certainty during the operating life of the system,
5. greatly improved pipe insulation techniques for steam system valves and flanges,
6. greatly improved steel furnace skid rail thermal insulations,
7. better data on the emittance properties of high-temperature thermal insulations and weather barrier materials,
8. data on changes that occur to the total emissivity of high-temperature insulations during service life,
9. data on changes that occur to the thermal conductivity of high-temperature insulations during service.

Another problem area that was identified involves thermal insulations for use in liquefied natural gas (LNG) land-based storage tanks and sea-going LNG tankers. Several of these installations have been constructed with polyurethane foam used as the thermal insulation. Moisture permeation and subsequent loss of insulation quality due to ice formation have been observed. Two instances were identified in which two tankers were being built and insulated, one with balsa wood and the other with foamed polystyrene rather than polyurethane. The combustion potential of large tankers and storage vessels when insulated with polyurethane foam was cited as an item of concern by several contacts. One large LNG distributor has banned polyurethane-insulated tankers from their terminals.

From the foregoing, it is clear that the thermal conductance properties of available thermal insulations must be better understood as a function of service conditions and service life. For the case of pipe and tank insulations, the performance must be regarded from a total system point of view, including the environmental barrier system, mastics, joint design for the insulation, installation practice, and the thermal transfer properties of the insulation material. A more quantitative understanding of the role of each of these variables on insulation system performance will be required before systematic and predictable improvements in energy conservation in the low and intermediate temperature ranges can be effective. For the case of high-temperature applications, the insulation

must also be regarded from a system point of view. The thermal performance of aluminosilicate and single-oxide fibrous insulations should be quantitatively demonstrated in various furnace wall designs for selected environments as soon as possible and the results of these performance tests given wide distribution. Similarly, insulating firebricks should be examined as to property and performance variability and a critical study made to determine the possibility of significantly reducing the thermal transport for various classes of IFB. Current furnace wall designs should be examined to establish if heat transfer through the walls can be better utilized than in the current practice of allowing the heat to flow through to the cold face and be lost. This might be accomplished via heat recuperator channels within the walls. Insulation systems for aluminum reduction and remelting, iron reduction, and steel reheating should be critically examined and improved via furnace design improvements and insulation improvements, followed by quantitative field demonstrations of these improvements.

Field demonstrations in these areas have typically been accomplished outside the Federal sector. They have typically resulted from agreements between an interested potential insulation user and an insulation or refractory vendor. Because of cost and time constraints, the user is forced to rely heavily on vendor-supplied data and by necessity usually chooses one insulation and/or refractory for actual demonstration. Results from such demonstrations may be made known or restricted depending on the value of the results to the user-demonstrator. This process results in a relatively slow dissemination of such information.

Selected field demonstrations supported entirely or in part with Federal funds with subsequent rapid dissemination of the quantitative results to industry could be one technique for relatively rapid performance comparisons of thermal insulations and thermal insulation systems.

3.5 REFERENCES

1. W. O'Keefe, "Thermal Insulation," *Power* 118(8): 21-44 (August 1974).
2. J. G. Myers et al., *Energy Consumption in Manufacturing* (A Report to the Energy Policy Project of the Ford Foundation), Ballinger Publishing Company, Cambridge, Mass., 1974.
3. Battelle Columbus Laboratories, (Report to U.S. Bureau of Mines), DB-245579 AS, *Energy Use Patterns in Metallurgical and Nonmetallic Mineral Processing (Phase 4 — Energy Data and Flowsheets, High Priority Commodities)* (June 27, 1975):
4. Battelle Columbus Laboratories, (Report to U.S. Bureau of Mines), DB-246357 AS, *Energy Use Patterns in Metallurgical and Nonmetallic Mineral Processing (Phase 5 — Energy Data and Flowsheets, Intermediate-Priority Commodities)* (Sept. 16, 1975).
5. J. T. Reding and B. P. Shepard, *Energy Consumption: The Primary Metals and Petroleum Industries*, Dow Chemical Company, PB-241,990 EPA 650/2-75-032-b (April 1975).
6. J. T. Reding and B. P. Shepard, *Energy Consumption: The Chemical Industry*, Dow Chemical Company, EPA-650/2-75-032-a (April 1975).
7. J. T. Reding and B. P. Shepard, *Energy Consumption: Paper, Stone, Clay, Glass, Concrete and Food Industries*, Dow Chemical Company, EPA-650/2-75-032-c (April 1975).
8. J. T. Reding and B. P. Shepard, *Energy Consumption: Fuel Utilization and Conservation in Industry*, Dow Chemical Company, EPA-650/2-75-032-d (August 1975).
9. Shell Oil Company, *The National Energy Outlook*, 9th Printing, (January 1974).
10. J. K. Eklund and D. Baeu, "An Infrared Eye," *Ind. Res.* 17(4): 52-55 (April 1975).
11. Charles A. Berg, "Conservation in Industry," *Sci.* 184(4134): 264-70 (1974).
12. A. L. Chart and D. F. Stock, "Cost Factors Related to Energy-Saving Applications of Refractories," Harbison-Walker Refractories, Pittsburgh, Pa., (unpublished manuscript, October 1975).

4. ASSESSMENT OF ECONOMIC CONSIDERATIONS

4.1 INTRODUCTION

This chapter presents a brief review and summary of economic considerations and analytical procedures that currently exist in the thermal insulation field. Many economically significant factors could also have been addressed in this study had the time been available; among these are labor costs for installing insulation systems, manufacturing cost variables, and health considerations in using insulation materials. As a prelude to the more detailed discussion of the analytical procedures, we mention several background factors that have special economic significance at this time.

4.2 BACKGROUND FACTORS AFFECTING INSULATION USE

One of the most dramatic changes in recent years is in fuel price increases that have occurred since the early 1970s. Such rapid price increases have improved the economic value of fuel conserving practices such as use of thermal insulation. However, in making analyses of the economic value of insulation over lifetimes of 10 to 15 years, assumed fuel escalation rates become very speculative. Therefore the sensitivity of economic insulation thickness to projected fuel prices is of interest to companies as they plan for future expansion of production facilities.

Another factor that can affect the use of thermal insulation is the availability of a traditional industrial fuel, such as natural gas. With the supply of natural gas for industry becoming more questionable in times of high domestic demand, the efficient use of insulation can become an important factor in retaining production continuity for industries dependent on natural gas, such as steel and industrial chemicals.

As a result of the Arab oil embargo and the emphasis on national independence of energy supplies, energy conservation in industrial processes has received much attention. The potential for reducing the waste energy is being realized in most industries; also, national goals for energy conservation are stimulating the use of more efficient processes. Hence, the application of thermal insulation to economically justified

thicknesses is one measure that industrial companies can take to improve conservation of energy in the immediate time frame.

4.3 ASSESSMENT OF ECONOMIC INSULATION THICKNESS ANALYSES

The value of insulation in industrial processes is derived from several different economic benefits. Direct economic benefits or savings result from conservation of fuel, conservation of products, and increased production of products. Indirect economic benefits are obtained from better control of temperature and protection of personnel from hot surfaces. The economic value of industrial insulation from the direct benefits appears to be so obvious that one expert in the field has stated that the question is not *whether* to insulate but *how much* insulation is justified. The objective of this section, then, is to briefly review (1) the traditional procedure used to determine what insulation thickness is economically justified -- the "economic thickness"; (2) the application of economic thickness analyses by the Thermal Insulation Manufacturers Association (TIMA) and by industrial companies; and (3) current economic conditions and considerations that were found to be important to industrial users of insulation.

4.3.1 Traditional Analysis of Economic Thickness

One of the first analytical procedures for calculating the economic thickness of insulation was presented by L. B. McMillan in 1926 at a meeting of the ASME. The detailed development of McMillan's economic thickness analysis is readily available in Malloy's book¹ and hence is not reproduced here. However, some of the more important features of this analysis procedure are presented before reviewing the present status of economic evaluations of industrial users and TIMA.

The basic cost factors incorporated in the traditional analysis of economic thickness of insulation are grouped into two types. One type of cost factor decreases with additional insulation thickness, reflecting cost savings from additional insulation use. Such decreasing cost factors for a new plant are:

1. cost of fuel and/or purchased power,
2. capital investment in heat (or cold) producing and distributing equipment,

3. value of money for capital investment,
4. interest on investment,
5. marginal maintenance cost for plant equipment.

The cost factors that increase with additional insulation thickness are similar to the decreasing factors, as follows:

1. capital investment for installed insulation,
2. value of money for investment,
3. interest on investment,
4. marginal maintenance cost for insulation.

To compare the increasing and decreasing costs for a specific insulation configuration, all cost factors are put on an annual average basis using assumed lifetimes or depreciation periods for the plant and insulation investments. Appropriate average values of fuel and maintenance costs are chosen by the analyst and may reflect escalation of such costs over the project life. Another cost factor chosen at the discretion of the analyst is the capital investment money value, expressed as a percent per year of the capital investment. This factor represents a value of capital to a company on the basis of the potential investment options available to the company. (Similar economic terms for the value of money for invested capital are the "required rate-of-return" and the "discount rate.")

The criterion for selecting the economic thickness of insulation is based on the simple concept of determining the first 1/2-in. (13-mm) thickness increment for which cost increase equals or exceeds cost decreases. Referring to Fig. 4.1, the economic thickness occurs at the minimum total annual cost since the "lost heat" cost and "insulation" cost are monotonically changing cost functions. McMillan's economic thickness derivation was therefore based on analytically determining the insulation thickness at which the minimum total annual cost occurs.

4.3.2 Cost Savings from Insulation Capital Investment

In addition to the minimum total cost criterion of McMillan's analysis, industrial companies often include the requirement that the reduction in "lost heat cost" be a certain percentage per year of the capital invested

Fig. 4.1. Economic Thickness of Insulation. Provided by Thermal Insulation Manufacturers Association and reproduced by permission.

in insulation over the life of the insulation. This criteria is called the required return-on-investment (ROI) and can be applied to either the entire insulation thickness or the last 1/2-in. (13-mm) increment. In the former case, the ROI is an overall value representing the total savings from an uninsulated condition; for the latter case, the ROI is an incremental value for the last 1/2 in. of additional thickness. By requiring a minimum incremental ROI, a company may be assured that each additional increment of insulation can produce savings that are at least competitive with alternate investments. However, the minimum incremental ROI can be set so high that the economic thickness, in terms of minimum total cost, is not reached. Then the minimum required ROI becomes the criterion that determines the maximum insulation thickness justified economically.

From Fig. 4.1, one can see that the incremental savings decrease and the insulation investment increases with additional insulation thickness. For a new plant, the overall ROI for insulation typically decreases from several hundred percent per year for the first increment of insulation thickness to about 100%/year at the economic thickness. Such ROI values result largely from the fact that, except for small pipes, total invested capital for insulation and process heat generating capacity decreases with the use of insulation at the economic thickness relative to the uninsulated condition (see Malloy¹). Even with no savings credited for the reduction in steam generating capacity investment, overall ROI values (from Malloy¹) for 1/2-in. (13-mm) pipe insulated to the economic thickness ranged from 19% per year at 100°C (212°F) to greater than 200% per year above 480°C (900°F). In addition to the attractive ROI values obtained for the overall economic thickness of insulation, incremental ROI values were reported¹ to be at least 19% per year for the last 1/2-in. thickness increment at the economic thickness. The return-on-investment values reported by Malloy¹ are from studies performed with early 1960 economic cost conditions. Although no additional economic calculations were performed as a part of this assessment, we believe the current return-on-investment potential for industrial insulations to be comparable to, if not better than, the ROI for early 1960 conditions.

4.3.3 Discounted Cash-Flow Investment Analysis

The discounted cash-flow (DCF) method is a more sophisticated method being used by some industrial companies to analyze the profitability of investments in various situations. Cash flow refers to the timing of disbursements and receipts for capital and operating costs and earnings or savings during the assumed lifetime of the project. The main advantage of the DCF method over the average annual cost method employed in McMillan's original analysis is that the effect of timing of capital expenditure on resulting earnings is accounted for.

All the cost factors used in McMillan's analysis are also used in the DCF method. The value of money is represented by an assumed "discount rate," which is applied to all cash flows to put them on the same

"present value" basis. When all present value cash flows are summed over an assumed project life, the "net present value" (NPV) of the project investment is obtained. The prime objective of this method is to determine a discount rate for which the NPV equals zero at the end of the assumed project life. The discount rate for this condition is called the discounted rate-of-return (DRR). Stated another way, when the DRR is equal to an assumed discount rate, then the risk is zero for not recovering the invested capital during the project lifetime. (See Bierman and Smidt² for more detailed discussion of the DCF methodology.)

The DCF method is discussed because the DRR is used in a manner similar to the incremental ROI to determine how much insulation is economically justified. Companies employing the DCF method also use it to compare the profitability of different capital investments.

4.4 COMPUTER ANALYSIS PROGRAMS

The economic thickness solution developed by McMillan requires an iterative solution involving the total monetary value of heat, the cost of insulation per unit of thickness, the physical dimensions of the system, the external thermal resistance, insulation thermal conductivity, and the operating and ambient temperatures. With so many variables involved, the use of computers to calculate the economic thickness was an essential step in applying McMillan's analysis to the wide range of real-world insulation conditions. A joint computer calculational effort between Union Carbide Corporation and the West Virginia University produced a manual, which was published³ by the National Insulation Manufacturers Association (NIMA) in 1961. This calculational program was greatly simplified by the observation that insulation cost at a specific time and location increases linearly with thickness, with a constant value for the intercept at zero thickness.

Subsequent to the NIMA publication of 1961, an updated economic thickness manual,⁴ called ECON-I was published in 1973 by the Thermal Insulation Manufacturers Association (TIMA). It followed the same calculational procedure that was used in the NIMA manual with the

following differences. The NIMA manual required the user to determine the average annual heat and maintenance costs on whatever basis he chose. However, ECON-I internalized a 7.5%/year interest rate and an annual insulation maintenance cost of 1% of the total plant investment. A heat cost escalation rate of 4%/year was also included in ECON-I with the capability to adjust for escalation rates up to 10%/year. Base insulation cost factors were also updated to 1973 conditions in ECON-I.

In 1975, TIMA published⁵ an economic thickness manual called R-ECON for adding or retrofitting insulation thickness to the economic value projected at that time. It followed the same calculational procedure as ECON-I with new values assumed for the following variables: 7%/year escalation rate on heat cost; 10%/year interest rate; \$20 per lb/hr (\$44 per Kg/hr) of steam generating capacity. In addition, the range of heat cost was limited to \$2.20 per 1000 lb (\$484/metric ton) of steam $\pm 20\%$, and the selection of insulation cost was limited to three values: a base cost, base cost + 25%, and base cost + 50%. Therefore, R-ECON updated some of the economic data to more current values but at the same time restricted the range of several important cost factors.

In our contacts with large industrial users of insulation and also engineering consulting firms, we found little or no use being made of the R-ECON and ECON-I manuals for economic thickness at the present. The reasons for this lack of use varied greatly. The most important reasons are listed below.

1. Confidence was lacking in the procedure for adjusting insulation costs for different thicknesses and specific installation conditions. Many companies keep insulation cost data for their locality and installation conditions so that they can more accurately determine economic thickness with their company computer programs.

2. Flexibility was lacking in investigating cost of money factors. Many companies wish to explore the sensitivity of capital investment projects to variations in the cost of money.

3. Discounted rate-of-return and net present value are used for company investment decisions. Companies using this method will analyze investment in insulation in the same way other investments are analyzed.

4. Economic thickness specified by ECON-I or R-ECON can be impractical to apply in some cases. This situation results in not using the recommended results rather than not using the procedure. The nature of the problem is that such large thicknesses are specified that confinement occurs between pipes in pipe runs and between nozzles on tanks.

A very recent development in computer analysis of economic insulation thickness is a design manual⁶ being developed by York Research Company for the Federal Energy Administration and is expected to be available in the spring of 1976. The first draft of this manual was reviewed briefly. The calculational procedure incorporates several features that may make it useful to industrial users. First, the discounted cash-flow method is used to obtain the economic thickness and net present value basis. Second, insulation cost factors input by the user allow for single, double, and triple layers and also for three complexities of pipe fittings. Third, cost of money and other cost factors can be varied independently over a wide range.

4.5 SURVEY OF ECONOMIC CRITERIA OF INDUSTRIAL USERS

Many industrial companies contacted during our survey discussed several economic criteria that apply to current investment decisions.

For companies using discounted cash-flow analysis, the discounted rate-of-return (DRR) required for new capital projects traditionally ranged from 10 to 15%/year. However, with increasing competition for capital, some companies have increased their required DRR to 30 to 50%/year. Even with such high earnings requirements, insulation investment has been justified for the economic thickness determined on a minimum total cost basis. In some petroleum refining companies, the required DRR for energy conserving investments such as insulation have been reduced to about 15%/year. Again, investment in thermal insulation usually meets such a requirement.

The pay-back period is a traditional measure of the time required to recoup invested capital. Where payback periods have traditionally been required to be five to six years, in many instances the required

payback period has been reduced to one to two years. Many additions of insulation thickness cannot meet such a short period requirement. However, insulation of bare valves, flanges, and tanks usually can satisfy a one to two year payback period requirement.

The final and basic economic criterion that current investment projects must satisfy is simple availability of the capital to proceed with a project. Even though an investment may be judged desirable on a profitability and short payback basis, in some cases, the lack of available capital at acceptable interest rates has postponed further use of insulation during current economic conditions.

4.6 OBSERVATIONS AND CONCLUSIONS

As a result of the survey of industrial users of thermal insulations, contact with consultants, and our brief review of economic analysis applied to thermal insulation, we have made the following observations and conclusions.

1. Insulation of all heated surfaces — such as flanges, valves, and tanks — not presently insulated is economically justified for surfaces other than in waste streams.
2. Availability of investment capital is currently restricting many companies from upgrading insulation and other process improvements.
3. Analysis of economic insulation thickness can lead to optimistic financial savings if the analysis uses unrealistic service life and thermal conductivity values. Achieving the desired service life emphasizes good design, installation, and maintenance procedures; realistic thermal property information emphasizes the importance of realistic data for service conditions (see Chap. 5).
4. Many different economic criteria are used for making investment decisions in industrial companies. These criteria range from the simple payback period and return-on-investment to the discounted-rate-of-return based on discounted cash-flow analysis.
5. Thermal insulation investment in new plants is justified to the economic thickness even with 30 to 50%/year discounted rates-of-return required.

6. ECON-I and R-ECON manuals for calculating economic insulation thickness are generally not used by large industrial companies contacted in this assessment. Such companies use economic analysis programs that are more flexible, better understood, and hence more trusted. Also the results from ECON-I and R-ECON often indicate such great insulation thicknesses as to be impractical because of physical confinement between equipment.

4.7 REFERENCES

1. J. F. Malloy, *Thermal Insulation*, Chap. 2, pp. 89-126, Van Nostrand Reinhold Company, New York (1969).
2. H. Bierman, Jr. and S. Smidt, *The Capital Budgeting Decision-Economic Analysis and Financing of Investment Projects*, 2nd ed., The MacMillan Company, New York, 1966.
3. *How to Determine Economic Thickness of Insulation*, National Insulation Manufacturers Association, New York, N.Y. (1961).
4. *ECON-I, How to Determine Economic Thickness of Thermal Insulation*, Thermal Insulation Manufacturers Association, 7 Kirby Plaza, Mt. Kisco, New York, 1973.
5. *R-ECON, A Method for Determining Economic Thickness of Add-On Thermal Insulation*, Thermal Insulation Manufacturers Association, 7 Kirby Plaza, Mt. Kisco, New York, 1975.
6. "Industrial Insulation Design and Assessment Manual" (Draft), York Research Corp., FEA Contract CO-04-50169-00, J. Hofbaner, Project Manager, FEA, Washington, D.C.

5. ASSESSMENT OF HEAT TRANSMISSION INFORMATION FOR THERMAL INSULATIONS

5.1 INTRODUCTION

This chapter is a review of some of the many facets of heat transmission through thermal insulations that have been uncovered in the course of this project from open literature publications, company brochures, and personal contacts. By no means is this chapter a complete accounting of insulation properties. Most knowledge on insulations has been obtained by work near room temperature, with subsequent measurements and applications at higher and lower temperatures generally being outgrowths of studies at ambient temperatures. For this reason we choose to discuss insulations generally, without necessarily distinguishing between building and industrial insulations. For instance, we believe knowledge of the mechanisms of heat transmission operative in insulations and subsequent control of the factors that influence these mechanisms form an integral part of any insulation application, be it building or industrial.

Clearly, advances in insulation technology must involve a circuit with information feedback connecting the three areas — material development, subassembly tests, and field evaluations. Our assessment found that the documentation of knowledge decreases as one moves toward field evaluations, forcing this review to deal with the material development area. Despite this shortcoming there is sufficient information and lack of information to warrant considerable discussion and concern about insulation heat transmission.

Thermal insulations include a wide variety of materials that may be considered mixtures of gases and solid bodies, which in large measure owe their insulating value to the low thermal conductivity of the gas phase. As noted in Chap. 3, the insulation may be fibrous, granular, cellular, or multilayered and used as evacuated or unevacuated systems. They exhibit the range of thermal conductivity values k , from 10^{-5} to $10 \text{ W m}^{-1} \text{ K}^{-1}$ (7×10^{-5} to $7 \text{ Btu in. hr}^{-1} \text{ ft}^{-2} \text{ }^{\circ}\text{F}^{-1}$) as shown in Fig. 5.1 taken from Pratt.¹ Specific insulations show various thermal conductivity

Fig. 5.1. Range of Thermal Conductivities of Low-Conductivity Materials at or Near Room-Temperature. Reproduced from Pratt¹ by permission of Academic Press.

values and temperature dependences, as depicted in Fig. 5.2 (Pratt¹), depending on the heat flow contribution of four basic mechanisms:

1. solid conduction through the materials forming the insulation, k_s ;
2. radiation transfer through the voids and the components of the insulation, k_r ;
3. gas conduction within the voids, k_g ;
4. convective transfer in and through the voids, k_m .

Fig. 5.2. Relationships Between Thermal Conductivity and Temperature for Typical Thermal Insulations and Other Low-Conductivity Materials. Reproduced from Pratt¹ by permission of Academic Press.

This chapter and its appendices deal with the role of the ASTM and industry in insulation, equipment used to measure insulation thermal conductivity, the information background on heat transmission depicted in Figs. 5.1 and 5.2, the heat flow mechanisms, and factors that change the heat transmission behavior of insulations.

Two further points of perspective should be made. The thermal conductivity of an insulation has an important bearing on the use of a given insulation; however, this is just one of many properties that are needed for an insulation decision.² We have used the term, thermal conductivity, (k) to describe the heat transmission value for an insulation. As explained later this term may or may not be appropriate, depending on the material, test conditions, and usage factors. In fact, balloting is currently occurring on ASTM specifications C 177 and C 518, in which the term thermal conductivity is deleted from the texts.

5.2 ASSESSMENT OF ASTM ACTIVITIES

The American Society for Testing and Materials (ASTM) serves as a focal point for many insulation interests in the U.S.A. ASTM committees C-8 and C-16 are particularly interested in property measurements on insulations. Committee C-8, entitled Refractories, Glass, Carbon and Other Ceramic Materials, has primary interest in refractory materials, which may or may not be thermal insulations but are generally to be used above 650°C (1200°F), whereas committee C-16, entitled Thermal and Cryogenic Insulating Materials, is concerned with thermal insulations, generally for but not restricted to use below 650°C (1200°F). Membership of these committees includes manufacturers, users, and measurers, who are interested in standards and tentative specifications, methods of test, recommended practices, definitions, and related materials, such as proposed methods. Parts 17 and 18 of the 1974 books of ASTM Standards³ include the standards of C-8 and C-16, respectively. These committees hold business meetings semiannually to accomplish their assigned tasks, and they have made significant contributions to insulation technology. Actually, two subcommittees, C-8.04 and C-16.30, have responsibility for maintaining and updating the prescriptions for several methods of testing

the heat transmission characteristics of insulation. The ASTM methods and responsibilities are indicated in Table 5.1.

Table 5.1. ASTM Thermal Methods and Committee Responsibilities

Designation	Title
<u>Subcommittee C-16.30 — Chairman, R. P. Type (Dynatech R/D Co., Cambridge, Mass.)</u>	
C 177-71	Thermal Conductivity of Materials by Means of the Guarded Hot Plate
C 518-70	Thermal Conductivity of Materials by Means of the Heat Flow Meter Method
C 236-66	Thermal Conductance and Transmittance of Built-Up Sections by Means of the Guarded Hot Box
C 335-69	Thermal Conductivity of Pipe Insulation
C 691-71	Thermal Transference of Nonhomogeneous Pipe Insulation at Temperatures Above Ambient
C 745-73	Heat Flux Through Evacuated Insulations Using a Guarded Flat Plate Boiloff Calorimeter
<u>Subcommittee C-8.04 — Chairman, W. C. Bohling (Babcock and Wilcox, Co., Augusta, Ga.)</u>	
C 201-68	Thermal Conductivity of Refractories

Application of these methods has assisted in maintaining a degree of uniformity in insulation testing. However, this project continually heard the remark, "Remember these specifications represent a lowest-common denominator of concerns, and can be misapplied and yield misleading results." Commensurate with this is the ASHRAE comment⁴ about the Guarded Hot Plate method (ASTM designation C-177), "The accurate determination of fundamental conductivities and conductances requires considerable skill."

The ASTM Committee C-16 has sponsored four symposia that deal with thermal insulations over a broad temperature range.⁵⁻⁸ Appendix B provides a description of these symposia as well as a materials index for the four symposia. The index illustrates the diversity of insulations.

The initial paper in the proceedings⁸ of 1973 ASTM Symposium was authored by the ASTM Subcommittee C-16.30 and entitled, "What Property Do We Measure?" This paper discusses the philosophy of the measurement of heat transfer properties of insulation and the manner in which certain

heat transfer properties are used or possibly misused in describing thermal insulation performance. The C-16.30 Subcommittee goal is to provide prescriptions of methods that measure applicable characteristic properties of insulations. Thus a material's thermal performance is determined at or near the conditions of actual use. In contrast, the practice in other countries is aimed at measuring theoretical properties of the material, which allows calculation of thermal performance. In effect, the procedures used by other countries aim to obtain the thermal conductivity of the material, whereas the C-16.30 methods yield a thermal conductance, which — depending on the material, the test conditions, and test results — may or may not be the material's thermal conductivity. Understanding this is a most important consideration where heat transmission includes convective or radiative effects, which is the case for many insulations.

The prescriptions described by C-16.30 include conversion factors for various thermal conductivity units, and they recommend use of SI units for k , $\text{W m}^{-1} \text{K}^{-1}$, and thermal conductance, $\text{W m}^{-2} \text{K}^{-1}$. In contrast, most industrial brochures use English units for k , $\text{Btu in. hr}^{-1} \text{ft}^{-2} \text{°F}^{-1}$, and Europeans use $\text{kcal m}^{-1} \text{hr}^{-1} \text{°C}^{-1}$. This diversity of units impedes efficient communication and increases the chance for error in calculations.

Brief descriptions and comments about the various ASTM methods listed in Table 5.1 are provided in Appendix C. Detailed information on all these techniques is available at a nominal cost from the ASTM. In almost every case the ASTM prescription is miniscule compared with the volume of literature that covers studies and uses of the methods. Some knowledge of the experimental techniques is needed to gain a perspective of the data they obtain.

The ASTM Standards emphasize that the methods are to be used for samples dried to a constant weight before testing. It should be recognized that the thermal conductivity obtained will not necessarily apply, without modification, to service conditions. In addition to the moisture question, other factors, such as mean temperatures that differ appreciably from that of the test, a density significantly different from the test sample, or for some materials, the effect of temperature difference, could be appreciable. Thus, the *user* should be extremely cautious.

In 1974 the ASTM C-16.30 subcommittee released results of an equipment and standards survey obtained by contacting known users of thermal conductivity equipment in the U.S.A. and abroad. Appendix D contains the survey results, a rearrangement by the authors, and a discussion of this needed effort. The primary intent of the survey was to select reference materials of low k to be used as standards. While much valuable information was obtained, the much-needed primary intent remains illusive.

While the ASTM methods are generally acceptable to industry, a wide variety of other k -measuring apparatuses have been used successfully to study insulating materials. Appendix E contains a description of some of these which include radial heat flow methods, flat plate or disk methods, and transient methods.

The content of these appendices (B, C, D, E) forms an integral part of our knowledge of thermal insulation. Exiling this material to appendices was done only to enhance the readability of this report.

5.3 ASSESSMENT OF INSULATION INFORMATION

For a subject as broad as thermal insulations, it is not surprising that a tremendous amount of information is available. The quality of the information, however, is almost impossible to assess for the simple reason that there is such a wealth of data on such a variety of materials. If, for example, the available data for a single type or class of industrial thermal insulation were plotted, the paper would be essentially black with points and curves. Therefore, each user will tend to pick a single source of information depending upon his own background and training. Typical resource materials might be the *Handbook of Chemistry and Physics*,⁹ Mantell's *Engineering Materials Handbook*,¹⁰ Mark's *Handbook*,¹¹ Norton's *Refractories*,¹² Perry's *Chemical Engineer's Handbook*,¹³ or the *ASHRAE Handbook of Fundamentals*.⁴ Unfortunately, each of these sources is incomplete to a lesser or greater extent since they do not address all the pertinent properties of the materials such as strength, permeability, expansion, pH, combustibility, thermal shock resistance, etc. that might be especially important for a particular design or installation.

Examples of the information that one typically finds in the literature^{4,14} for thermal conductivity are shown in Table 5.2 and Fig. 5.3. As a general rule, much more may be found for k of insulations than for the other properties. The reader might take particular note of footnote a of Table 5.2.

Table 5.2. Example of Published Information on Thermal Conductivity of Insulation Materials. Reproduced from *ASHRAE Handbook of Fundamentals*,⁴ by permission of the American Society of Heating, Refrigeration, and Air-Conditioning Engineers, Inc.

Thermal Conductivity (k) of Industrial Insulation (Design Values)^a (For Mean Temperatures Indicated)
Expressed in Btu per (hour) (square foot) (Fahrenheit degree temperature difference per in.)

Form	Material (Composition)	Accepted Max Temp for Use, ° F	Typical Density (lb/cu ft)	Typical Conductivity k at Mean Temp F															
				-100	-75	-50	-25	0	25	50	75	100	200	300	500	700	900		
BLANKETS & FELTS	MINERAL FIBER (Rock, Slag, or Glass) Blanket, Metal Reinforced	1200 1000	6-12 2.5-6											0.26	0.32	0.39	0.54		
														0.24	0.31	0.40	0.61		
	Mineral Fiber, Glass Blanket, Flexible, Fine-Fiber Organic Bonded	350	0.65 0.75 1.0 1.5 3.0				0.23	0.26	0.27	0.28	0.30	0.32	0.42	0.58					
							0.23	0.26	0.27	0.28	0.29	0.30	0.40	0.57					
							0.23	0.24	0.25	0.26	0.27	0.28	0.36	0.51					
							0.22	0.23	0.24	0.24	0.25	0.26	0.32	0.44					
							0.20	0.21	0.22	0.22	0.23	0.24	0.29	0.39					
	Blanket, Flexible, Textile-Fiber Organic Bonded	350	0.65 0.75 1.0 1.5 3.0				0.27	0.28	0.29	0.30	0.31	0.32	0.50	0.68					
							0.26	0.27	0.28	0.29	0.31	0.32	0.48	0.66					
							0.24	0.25	0.26	0.27	0.29	0.31	0.45	0.60					
BLOCKS, BOARDS & PIPE INSULATION	Felt, Semi-Rigid Organic Bonded	400 850	3-8 3											0.24	0.25	0.26	0.27	0.35	0.44
	Laminated & Felted Without Binder	1200	7.5	0.16	0.17	0.18	0.19	0.20	0.21	0.22	0.23	0.24	0.35	0.55			0.35	0.45	0.60
	VEGETABLE & ANIMAL FIBER Hair Felt or Hair Felt plus Jute	180	10									0.26	0.28	0.29	0.30				
	ASBESTOS Laminated Asbestos Paper Corrugated & Laminated Asbestos Paper	700	30											0.40	0.45	0.50	0.60		
	4-ply	300	11-13											0.54	0.57	0.68			
	6-ply	300	15-17											0.49	0.51	0.59			
	8-ply	300	18-20											0.47	0.49	0.57			
	MOLDED AMOSITE & BINDER	1500	15-18											0.32	0.37	0.42	0.52	0.62	0.72
	85% MAGNESIA	600	11-12											0.35	0.38	0.42			
	CELLULAR GLASS	1200	11-13											0.32	0.37	0.42	0.52	0.62	0.72
	DIATOMACEOUS SILICA	800	9											0.42	0.48	0.55			
		1800	21-22														0.64	0.68	0.72
		1900	23-25														0.70	0.75	0.80
	MINERAL FIBER (Rock, Slag, or Glass) Organic Bonded, Block Non-Punking Binder Pipe Insulation	400 1000 350 500	3-10 3-10 3-4 3-10	0.16	0.17	0.18	0.19	0.20	0.22	0.24	0.25	0.26	0.33	0.40					
	Inorganic Bonded-Block	1000 1800	10-15 15-24					0.20	0.21	0.22	0.23	0.24	0.29						
	Pipe Insulation	1000	10-15					0.20	0.22	0.24	0.25	0.26	0.33	0.40					
	CORKBOARD (Without Added Binder)	200	6.5-8					0.24	0.25	0.26	0.27	0.28							
	CORKBOARD (Without Added Binder, Pipe Insulation)	200	7-10					0.25	0.26	0.27	0.28	0.29							
	PLASTIC FOAMS Flexible Elastomeric Rigid, Polystyrene, Extruded	200 170 170	5-9 2 1	0.17	0.18	0.19	0.20	0.21	0.22	0.23	0.25	0.26							
	Molded Beads	210	1.5-2.5	0.18	0.20	0.21	0.23	0.24	0.25	0.27	0.28								
	Polyurethane ^{as} R-11, Exp.	150	4.5	0.14	0.15	0.16	0.17	0.17	0.17	0.16	0.17	0.18	0.21						
	RUBBER, Rigid Foamed							0.20	0.21	0.22	0.23								
	VEGETABLE & ANIMAL FIBER Wool Felt (Pipe Insulation)	180	20					0.28	0.30	0.31	0.33								
	INSULATING CEMENTS																		
	MINERAL FIBER (Rock, Slag, or Glass) With Colloidal Clay Binder With Hydraulic Setting Binder	1800 1200	24-30 30-40										0.49	0.55	0.61	0.73	0.85		
													0.75	0.80	0.85	0.95			

^a Representative values for dry materials as selected by the ASHRAE Technical Committee 2.4 on Insulation. They are intended as design (not specification) values for materials of building construction for normal use. For the thermal resistance of a particular product, the user may obtain the value supplied by the manufacturer or secure the results of unbiased tests.

^b These temperatures are generally accepted as maximum. When operating temperature approaches these limits the manufacturer's recommendations should be followed.

^c These are values for aged board stock. For discussion on the change in conductivity with age of Refrigerant 11 expanded urethane see section on Factors Affecting Thermal Conductivity, Chapter 18.

Fig. 5.3. Apparent Thermal Conductivity Versus Temperature for Various Materials in Air at 1 atm (0.1 MPa). Reproduced from Glaser et al.¹⁴

The standard tests and specifications of the ASTM C-16 Committee on Thermal Insulations may be useful for defining, within rather broad limits, typical properties of a certain generic insulation. Figure 5.4 shows some of the k -values specified by the ASTM and the corresponding density ranges. It must be remembered, however, that the ASTM specifications are typically a "lowest common denominator," arrived at by committee consensus and do not describe a specific trade-name insulation. For example, the specification might call for maximum allowable

Fig. 5.4. Thermal Conductivities and Sample Densities According to the ASTM Specifications.³

density, a minimum strength, and a maximum conductivity. A product that meets the minimum strength requirement will have a lower density and a lower conductivity than required by the specifications. For another product, for which greater strength is required, the manufacturer will more closely approach the maximum density and maximum conductivity, and will far surpass the minimum strength. Thus, the ASTM specifications are not of great value as a source of information if more than one manufacturer produces a given product.

At the present time, the world's most complete compilation of thermophysical properties of materials is probably that of the Thermophysical Properties Research Center (TPRC*) at Purdue University,

*Now known as Thermophysical and Electronic Properties Information Analysis Center.

which covers high-temperature solid materials.¹⁵ The coverage of thermal insulations in this work, however, is weak, consisting of four spacecraft composite insulations, four organic foams, two inorganic foams, two inorganic powders, and the 1600 to 3100 IFB series. TPRC has recently issued a report¹⁶ that described polystyrene and polyvinyl-chloride thermophysical properties, including those of the foams above 100 K (-279°F).

A notable addition to the storehouse of knowledge on thermal insulations is a 1967 publication¹⁴ prepared under NASA contract by Arthur D. Little, Inc., entitled *Thermal Insulation Systems, A Survey*. The focus is on the more exotic insulation systems such as multifoils, but the report does include much useful information about all types of materials. The British-originated *Insulation Handbook*¹⁷ provides another useful compilation of properties and products. An extensive compilation of insulation properties was generated in 1962 under a USAF contract to Midwest Research Institute.¹⁸

It should also be noted that for those materials used at reduced pressure, the variation of conductivity with pressure is often presented. The most significant observation about these compilations is that the data spread may range up to a factor of 8 for a given generic material. A valid reason for a large portion of this data spread is the material itself. Over a period of time, a certain product will undergo significant alteration through changes in raw material and/or methods of manufacture. Thus, data for a "glass fiber blanket" actually represent a wide variety of samples from different manufacturers produced over a long time span. These factors, together with the uncertainties discussed in the appendices on measurement techniques, contribute to the observed spread in the data.

A significant quantity of property information on thermal insulations may be found in the open literature. More than 36 papers dealing directly with insulations have been presented at the 14 Thermal Conductivity Conferences held regularly since 1961. Publications arising from the regular meetings of the International Institute of Refrigeration

also contain much information. Not to be overlooked are the several Special Technical Publications of the ASTM and the whole host of technical journals such as those of the ASME, AIChE, ASHRAE, and American Ceramic Society, to name only a few. While much useful information is contained in all of these sources, it is difficult to assimilate. For example, in most instances, the materials tested are only poorly identified (e.g., from Manufacturers A, B, and C) and are even more poorly characterized. In addition, the experimental conditions are not suitably described with details such as surface conditions of critical apparatus components, temperature differences used, criteria of the experiment such as drift rates, and many other possible factors. The authors have encountered this same situation in much of the technical literature on thermophysical properties of all materials.

One source of information on insulations remains to be discussed: the manufacturer. By use of either his own testing facilities or outside laboratories he studies his own products (and those of his competitors) and distributes this information as technical sales literature and brochures. In addition, he normally includes a disclaimer to the effect that property values listed are typical, and products as supplied are subject to normal manufacturing tolerances. Unfortunately, these "normal manufacturing tolerances" are almost never quantified, but indications are that the product variability may easily reach 25%. We consider this to be one of the most limiting factors in the entire assessment of insulation information.

The best source of information on thermal insulations that the authors have found is Malloy's book, *Thermal Insulations*.¹⁹ Following a thorough discussion of the properties of insulations, Malloy states:

"Determining what insulation properties are important only indicates the information needed and provides the basis of investigation. The next question then becomes, how can these properties be measured and under what conditions should they be measured? Another question which follows is whether or not measurements made by laboratory test are truly indicative of the properties of the material in service. Does aging affect the

properties? If so, how much and at what rate? What effect does temperature have on test results? What effect does moisture content have on the properties?"

"Unfortunately, testing methods and studies of properties of material are not yet able to answer all these questions. Nor is there a laboratory available which is accepted as the authority on testing of properties of insulation materials. This statement does not imply that there are no standard test methods and laboratories to perform these standard test methods, but it does mean that the insulation industry lacks even the minimum requirements to provide reliable information. In many instances the manufacturers of insulation have developed their own test methods and can furnish some information regarding their materials. However, the test method used by one manufacturer is not always identical with that of another, so that the values of one cannot be compared with the results obtained by another. This makes direct comparison of material properties quite difficult. Another problem is that most of the mechanical properties are measured at atmospheric conditions and not at the temperatures to which the material is subjected in service. Inadequate information leads to poor design, the use of improper materials, and the installation failures to which the insulation industry has become accustomed."

"In recent years progress has been made in correcting this confusion and presently there exists a number of American Society of Testing and Materials Standard Test Methods. However, even with standard test methods, sometimes it is necessary, because of the wide range in characteristics, to perform more than one test for a single property, as one test may be incapable of measuring all the characteristics for the wide variety of insulation materials. Thus, duplication of test methods for a single property of insulations does exist and the proper selection must be made for the insulation being tested."

After listing more than 40 ASTM test methods applicable to insulations, Malloy continues:

"As can be seen from the above, standard test methods do not exist for all the properties of insulation listed previously. One reason is that some of these properties are difficult to determine. In other cases test equipment is quite expensive, few manufacturers or laboratories have the required equipment, and an industry standard has never been devised."

"It should be remembered that any laboratory test is a measure of a small sample. For certain characteristics, a small sample will provide an accurate appraisal, whereas for other materials the answer may only indicate the characteristics of that insulation. Other tests may attempt to predict the service life of insulation. Such service life tests are quite difficult to devise and evaluate. Yet this type of test is essential, and as the demand for it increases, eventually such tests will be devised by the industry."

The authors think that these statements present an accurate picture of the present state of the art regarding the property information on insulations.

Preceding the presentation of the very extensive tabulation of properties of all types of insulations, Malloy cautions the reader thus:

"Another factor which should be remembered in the use of these tables is that a particular generic material may be made by several manufacturers. As there are differences in the properties of a generic material produced by different manufacturers, the properties are a mean of the values listed for the products of the various manufacturers. Thus, for those products made by several manufacturers, no single manufacturer's product will have exactly the values as listed. It follows then, that these tables are presented to serve as a *guide* for selection of the correct *generic material* for an installation. However, the final choice of the particular manufactured product must be made by the individual by comparing competitive products."

The tables presented by Malloy are probably the most complete of all presently available, but significant gaps are obvious. Regarding these, he states:

"Hopefully, this book will indicate the need for more complete information on properties of materials and that any missing information will be made available by the manufacturers. When insulation consumers understand the need for designing insulation systems on a scientific basis the manufacturers will quickly respond by providing the necessary technical information."

In summary, we find that there is, on the one hand, a wealth of information available on thermal insulation properties, but on the other hand, a severe shortage of really useful, high-quality data and analysis. Probably the most serious paucity is a clear picture of the real product variability as supplied since this one factor has such a profound effect on the worth of all property information.

For a number of years the previously mentioned heat transmission measurement prescriptions and techniques have been applied to a variety of insulations to measure the effect of variables on heat transmission. Numerous effects have been identified, and mathematical descriptions of the phenomena have been suggested to describe the various heat transport processes acting in the insulations. One goal of such an approach is to obtain a useful understanding of the phenomena occurring in insulations and to alter or control the insulation characteristics to reduce the heat transmission. Indeed this technological approach has yielded improved insulations such as Min-K* and cellular materials, wherein the gas mean free path has been reduced, and superinsulations, wherein all conduction and convection components have been reduced by evacuation and the radiation component minimized by control of surface emittances. Another goal is to predict the behavior of an insulation from a relatively few input parameters; however, because insulations involve such a variety of materials assembled in a variety of structures, this approach may be too simplistic. The alternative is to measure each insulation under the conditions of use, but this is time-consuming, expensive, fraught with errors, and possibly capable of only limited advances in insulation technology.

*Trade name, Johns-Manville.

The theoretical studies on insulations have identified various mechanisms of heat transfer acting within the insulation. These mechanisms include: the solid components with their contact points, the gaseous conduction component and its characteristics, the radiative component and variables that alter it, and finally the gaseous convective component. Studies of these mechanisms are providing improved understanding of the behavior of insulations and, as indicated, often lead to new materials.

Appendix F provides a limited discussion of each of these mechanisms and some of the variables that change k of fibrous, granular, cellular, bulk, and multilayered insulations. The primary variables include temperature, density, moisture, gas, and pressure. Other variables studied include fiber dimensions, insulation thickness, fiber opacity, anisotropy, and aging effects. The studies quoted in Appendix F may provide the interested reader with some appreciation of the variability of insulation heat transmission characteristics.

5.4 OBSERVATIONS FROM MEASURERS

Throughout this survey many comments were received from various sources, as noted elsewhere in this report. A consensus comment concerning measurements was *"We try to do a good job and to get good results, but we're not so sure about everybody else!"* There is a general feeling that the ASTM methods can be misapplied, are somewhat too lax, and lack enforcement. Careful and definitive measurements are made by only a small number of laboratories. One manufacturer has an insulation center to provide expert advice on insulation, as well as an institute to school contractors.

Opinions expressed about the overall quality of insulation property data available from the manufacturers range from complete satisfaction to total distrust. Many persons felt that the manufacturers had obtained much data in their own laboratories or from various user experiences, but had not released the information. Some manufacturers and users claim that thermal conductivity tests are not of critical importance. However, this attitude may be fostered by the relatively high cost of

these tests. Also, one must recognize that product variability and test conditions are such that a single test may be meaningless. Some sources acknowledged that some manufacturers had detailed information about their products' variability, inferred from property correlations or determined directly by conductivity tests. However, this information is not made available to the user, so he must make an educated guess of probable maximum and minimum values for use in his design. This approach will almost surely lead to conservative and non-cost-effective designs.

A problem voiced by both manufacturers and users was the inapplicability of the various ASTM test procedures to the situation in the real world. To be specific, the procedures state that the materials will be tested in a dry condition, a rare state in many insulation installations. However, the manufacturers correctly claim that this dry condition is the only state that can be routinely reproduced in the laboratory and that it would be futile to attempt to duplicate the many and varied conditions that might exist in the field. Thus, the only guidance that the user has is the knowledge that the manufacturers' data are for dry conditions. His problem is then to estimate the degradation in conductivity caused by moisture or adsorbed gases and liquids. Careful experiments on this degradation have not been done for the obvious reason that they would be extremely difficult to perform and interpret. Therefore, we have an unresolved dilemma.

A second, specific complaint about the ASTM test procedures is that the smaller devices (most economical to construct and operate) allow tests on samples 25 mm (1 in.) or less in thickness, while practically all applications involve thicknesses greater than this. A thermal conductivity value (i.e., per unit thickness) is the result of the ASTM tests, while the user is more concerned with a thermal conductance (i.e., per total thickness). A conductance may, in principle, be calculated from a conductivity only if convective or radiative conduction processes are not operable in the particular case. A few manufacturers acknowledge this problem and have equipment to test useful thicknesses of insulations, while others claim such tests would be prohibitively expensive because of the size of the apparatuses required.

Some sources believe that the suppliers of cryogenic super-insulations are the leaders in the area of competence. This may, in large measure, be attributed to the large expenditure of funds for aerospace research in recent years. This segment of the industry has used a systems approach to an insulation installation. Thus, the design engineers for a cryogenic system are using data from their own company's laboratory plus knowledge gained from similar designs already executed. Since they are, in general, working toward a performance specification in the field, they are involved from beginning to end, and the customer is concerned only with the final result, not with the values used in the design. This is unique, and it would appear that this systems approach would be very advantageous to all users of thermal insulation, even for less critical applications.

Quite a different picture emerges at the opposite end of the temperature spectrum. The higher the temperature, the more ill defined insulation properties are. This may be attributed to the difficulties encountered in making very high-temperature measurements, to the absence of reliable reference materials, and to the lack of any firm theoretical basis for estimating or predicting property values. Indeed, one refractory ceramic manufacturer scrapped its C 201 refractory conductivity tester because the time and effort involved in measurements was considered unwarranted. Considering the tremendous interest in thermal insulation that has developed in the past few years, it is a curious anomaly that the Refractories Research Center at Ohio State University made only five tests on thermal insulations (four ceramic fiber blankets, one 2600°F IFB*) during the past year for various clients. Charles Semler, Director of the Center, was surprised at the rather small amount of testing requested since he had anticipated a much higher interest in high-temperature property information. This is not to say that the manufacturers are not concerned with high-temperature insulations, particularly the fiber blanket materials. Potential users

*2600°F IFB designates insulating fine brick capable of service up to 1400°C (2600°F).

certainly are, but they express strong doubts about the validity of the manufacturers' claims of the potential savings resulting from the application of these materials. One manufacturer has acknowledged the existence of these doubts and is presently constructing a special furnace with a 6 by 8 ft (1.8 by 2.4 m) instrumented test wall in order to make direct measurements of the thermal performance of various furnace wall constructions. It would seem to the authors that this approach to a systems tester is certainly a step in the right direction by the manufacturers and will yield much useful information. Another manufacturer has built a special mobile kiln to demonstrate the performance of ceramic fiber blankets.

Another indication of the level of interest in high-temperature insulations expressed by the manufacturers was their desire to conduct a round robin experiment on a fiber blanket material. This round robin would involve about eight laboratories, both manufacturers and private labs, and would be conducted on high-temperature guarded hot plates (C 177) and refractory testers (C 201). This comparison of methods and apparatuses is very timely and needed, in the author's opinion. A well-equipped unbiased laboratory is needed to coordinate this activity.

Germane to the discussion on ceramic fiber blanket insulation are comments from representatives of both C-8 and C-16 ASTM committees. The C-16 committee on thermal insulations, and particularly the C-16.30 subcommittee on measurements, has avoided the ceramic high-temperature insulations since this class of materials has been under the C-8 refractories committee. We find these two in conflict over the testing of ceramic fiber blankets and the operation of the C 201 tester. This needs to be resolved because these materials are becoming increasingly important, and the present situation may hinder development of needed standards and specifications.

The region extending from room temperature down to liquefied-natural-gas temperatures is a particularly troublesome one to the insulation user, more than to the property measurer. For this temperature range, organic foams, bulk loose-fill inorganics, or rigid inorganic forms of insulation are applicable. Herein lies the dilemma for the

insulation buyer since he is confronted with often conflicting information about the competing products. Comments from the users indicated that a major concern was not over the initial properties of the particular insulation, but rather was in the change in properties with time in service. The problem arises primarily from water vapor condensation and migration within the insulation. In many low-temperature applications, ice will form within the insulation, mechanically destroying it. The insulation manufacturers are certainly aware of this problem, but believe their responsibility is to provide insulation and barriers and to recommend good procedures for its installation. They realize that the properties of their material will be significantly altered (always degraded) by the condensed gases, but cannot qualify the magnitude of the effect because of the many variables. An insulation consulting engineer claims that some of the problems might be resolved if more realistic diffusion rates or permeabilities were quoted for products. He found moisture permeabilities 100 times greater than the stated values and attributed this difference to unrealistic test conditions.

In addition to property changes due to moisture, some materials — specifically the organic foams — double in thermal conductivity because of replacement of the foaming gas by air over a period of time. This is a natural diffusion process and is strongly temperature dependent. Users stated that this had occurred in their systems at a rate much faster than anticipated and required the installation of additional insulation to the system.

Several commentators took the manufacturers to task for the manner in which their property data was acquired. Manufacturers quote a *thermal conductivity* obtained using a temperature drop (ΔT) through the sample, which is quite proper under the ASTM procedures. Often the user is concerned with the *thermal conductance* of the insulation under the operating conditions, which typically involves a much larger ΔT . Thus, radiative heat transfer might become very significant, and the conductance could be much higher than indicated by the measured conductivity if the material is semitransparent at the wavelengths involved. This shows variability of applications and the importance of the details of

testing procedures and the problems that might arise if the manufacturer and the user do not fully understand all the implications in the numbers. The suggestion was made that the manufacturers should test under service conditions exclusively and so state in their literature. The manufacturers counter by stating that this information is available currently.

Much of the preceding discussion is also relevant to the intermediate temperature types of thermal insulations, although the variety of products becomes more limited as the temperature increases. Users encounter the moisture problem, but without the complication of ice formation. It is also in the temperature range that users are often more concerned with properties other than thermal conductivity. The comment was often made that the last property asked for was k . Within the compromises of an installation this may be reasonable since the k values for most insulations of a given temperature class are nearly the same. Manufacturers provide a product to fit a set of needs, with a k that is more of a compromise with other properties than a target.

Manufacturers and users generally feel that the thermal conductivity data for the insulations in the room temperature to intermediate temperature range are of reasonable quality. In this temperature range, however, we must recognize the possibility of radiative heat transfer and, as discussed earlier, must determine if the reported conductivities are realistic for the particular situation at hand.

The preceding indicates that, with the notable exception of the cryogenic segment, the whole insulation picture is clouded by fragmentation. That is to say, the person that makes the measurements is not really involved with their application; the designer is probably not familiar with the details of the measurements; the distributor fills orders; the installer follows his own practice; the customer gets an insulation system that may work; and if it doesn't, who does he turn to? Responsibility is divided and there is no logical overall control. One of the critical failings is that no one really follows the entire procedure to the logical conclusion of the job (i.e., a detailed testing and analysis of the insulation system as installed). Thus, the loop is not closed, and without this closure, the validity or quality of the

data, the design, and the installation cannot be assessed. Although it may be expensive, adoption of a performance specification approach for an insulation system, as is done in the cryogenics area, may be a fruitful area to pursue. Now may be the time to examine the merits of a move in this direction.

5.5 REFERENCES

1. A. W. Pratt, "Chapter 6: Heat Transmission in Low Conductivity Materials," pp. 301-405 in *Thermal Conductivity*, Vol. 1, ed. by R. P. Tyè, Academic Press, London, 1969.
2. W. C. Turner, private communication, November 14, 1975.
3. 1974 *Book of ASTM Standards with Related Material*, Part 17 (C-8) and Part 18 (C-16), American Society for Testing and Materials, Philadelphia.
4. *ASHRAE Handbook of Fundamentals*, Chap. 18 (p. 242), American Society of Heating, Refrigeration, and Air-Conditioning Engineers, New York, 1968.
5. *Symposium on Thermal Insulating Materials*, Am. Soc. Test. Mater. Spec. Tech. Publ. 119, American Society for Testing and Materials, Philadelphia, 1952.
6. *Symposium on Thermal Conductivity Measurements and Applications of Thermal Insulations*, Am. Soc. Test. Mater. Spec. Tech. Publ. 217, American Society for Testing and Materials, Philadelphia, 1957.
7. *Thermal Conductivity Measurements of Insulating Materials at Cryogenic Temperatures*, Am. Soc. Test. Mater. Spec. Tech. Publ. 411, American Society for Testing and Materials, Philadelphia, 1967.
8. *Heat Transmission Measurements in Thermal Insulations*, Am. Soc. Test Mater. Spec. Tech. Publ. 544, American Society for Testing and Materials, Philadelphia, 1974.
9. *Handbook of Chemistry and Physics*, 46th ed., The Chemical Rubber Company, Cleveland, Ohio, 1965-66.
10. *Engineering Materials Handbook*, 1st ed., ed. by C. L. Mantell, McGraw-Hill, New York, 1958.

11. *Mechanical Engineers' Handbook*, 5th ed., ed. by L. S. Marks, McGraw-Hill, New York, 1951.
12. F. H. Norton, *Refractories*, 3rd ed., McGraw-Hill, New York, 1949.
13. *Chemical Engineers' Handbook*, 3rd ed., ed. by J. H. Perry, McGraw-Hill, 1950.
14. P. E. Glaser et al., *Thermal Insulation Systems, A Survey*, NASA Spec. Publ. 5027, National Aeronautics and Space Administration, Washington, D.C., 1967.
15. *Thermophysical Properties of High Temperature Solid Materials*, Vol. 3, ed. by Y. S. Touloukian, The Macmillan Company, New York, 1967.
16. C. Y. Ho et al., *Thermophysical Properties of Polystyrene and Poly (Vinyl Chloride)*, CINDAS-TRPC Report 38 (August 1975).
17. *The Insulation Handbook 1973*, Lomax, Wilmoth and Company, London.
18. *Thermophysical Properties of Thermal Insulating Materials*, ASD-TDR-62-215, Wright-Patterson Air Force Base, Ohio, July 1962.
19. J. F. Malloy, *Thermal Insulation*, Van Nostrand Reinhold Company, New York, 1969.

APPENDIX A

INDUSTRIAL ORGANIZATIONS CONTACTED

**THIS PAGE
WAS INTENTIONALLY
LEFT BLANK**

A-1 INSULATION MANUFACTURERS CONTACTED

A-1.1 Individual Companies

Amspec, Inc.	Incell Corporation
A. P. Green Refractories Company	International Vermiculite Company
Babcock & Wilcox	Johns-Manville Corporation
Carborundum Company	Mobay Chemical Corporation
Celutex Corporation	Norton Company
Certain-teed Products Corporation	Owens-Corning Fiberglas
Christy Firebrick Company	Pittsburgh Corning Corporation
Dow Chemical	Plibrico Company
Eagle-Picher Industries, Inc.	Refractory Products Company
Fiber Materials, Inc.	Resco Products, Inc.
Fiberboard Corporation	Reynolds Aluminum Company
Forty-Eight Insulations, Inc.	Rock Wool Industries
General Refractories	Rock Wool Manufacturing Company
Harbinson-Walker	Spraycraft Corporation
Horizons, Inc.	U.S. Gypsum Company
ICI United States, Inc.	Zircar Products, Inc.

A-1.2 Manufacturer's Associations

- National Mineral Wool Insulation Association
- The Refractories Institute
- Thermal Insulation Manufacturer's Association

A-2 SYSTEM DESIGNERS CONTACTED

A-2.1 Architect-Engineers

- Arthur G. McKee and Company
- Badger Corporation
- Bechtel Power Corporation
- Ebasco Services, Inc.
- Sargeant and Lundy
- Stone and Webster Engineers

A-2.2 Consultants

O. A. Kelly
C. F. Lucks
W. C. Turner III

A-3 INSULATION USERS CONTACTED

A-3.1 Electric Power Utilities

Colorado Public Service	Philadelphia Electric Company
Commonwealth Edison Company	Southern California Edison Company
Duke Power Company	Tennessee Valley Authority

A-3.2 Steel

Armco Steel Company
Bethlehem Steel Corporation
Jones and Laughlin Steel Corporation
U.S. Steel Corporation

A-3.3 Nonferrous Metals

Aluminum Company of America
John Zinc Company
Reynolds Aluminum

A-3.4 Petroleum Refining

American Oil Company	Mobil Oil Corporation
El Paso Natural Gas Company	Phillips Petroleum Company
Exxon Oil Company	Shell Oil Company
Gulf Oil	Texaco Oil Company
Gulf Research and Development Company	

A-3.5 Industrial Chemicals

E. I. DuPont de Nemours and Company, Inc.
Exxon Chemical Company
Monsanto Chemical Corporation

The Dow Chemical Company
Union Carbide

A-3.6 Paper

Hammermill Paper Company
International Paper Company
Mead Corporation

A-3.7 Equipment Manufacturers

Temtek-Allied Division of Ferro Corporation
Thermon Corporation
Westinghouse Electric Corporation

A-3.8 Cryogenic Gases

Airco Cryopplants Corporation
Air Products
Cabot Corporation
Linde

A-4 MEASUREMENT LABORATORIES

Air Force Materials Laboratory
Babcock & Wilcox
Battelle Columbus Laboratories
Carborundum Company
C. F. Lucks
Celutex Corporation
Dynatech R/D Company
Harbinson-Walker
Johns-Manville

National Bureau of Standards
(Washington and Boulder)
National Research Council of Canada
Norton Company
Owens-Corning Fiberglas
Pittsburgh Corning Corporation
Refractories Research Center
Reynolds Metal Company

A-5 OTHERS CONTACTED

Battelle Columbus Laboratories

Corning Glass Works

Hartford Division — Emhart Corporation

Institute of Gas Technology

Kraft Foods

National Association of Home Builders

Pittsburgh Plate Glass

U.S. Bureau of Mines

York Research Corporation

✓

APPENDIX B

ASTM — SPONSORED SYMPOSIA

**THIS PAGE
WAS INTENTIONALLY
LEFT BLANK**

B-1 ASTM-SPONSORED SYMPOSIA

The four ASTM symposia on thermal insulations¹⁻⁴ contain about 39 papers that deal with applications, measurement techniques, various parametric effects, and mechanisms of heat transmission in insulation. These volumes provide a useful review of developments in the last 25 years in insulation technology. In many cases the work described was directed toward the need to solve a variety of applied problems, which include moisture effects in houses, large-scale industrial cryogenic operations, underground pipe insulations, spacecraft performance, and implantable artificial hearts. This range of topics and the different specific nature of each preclude any brief summary of the symposia; rather a few highlights of each are cited below.

The 1951 symposium consisted of five papers that summarized some of the first 12 years of activities of the C-16 committee. This included the result of a program of comparative thermal conductivity tests made in 17 different laboratories on corkboard at mean temperatures from -7 to 54°C (20 – 130°F) with 20 different guarded hot plates (GHP). This work stands as a hallmark in GHP technology and has not been duplicated to date. Other papers dealt with tests on moisture effects on heat flow in frame walls (F. A. Joy), radiant heat emission measurements in the infrared region (L. P. Herrington), room-temperature variations and the comfort and economy feature of high-heat-capacity wall constructions (Norman H. Spear), and results of tests that involve changing the operational limits of a 0.20-m (8-in.) GHP apparatus (C. F. Gilbo). Each of these topics was covered well and provided a basis for further papers in the later symposia.

The topic explored by Gilbo was the subject of four of the six papers at the 1957 symposia. Zeno Zabawsky described an improved 0.20-m (8-in.) GHP that incorporated a 32-junction thermopile for the guard-heater gaps and automatic temperature controllers to obtain a balance to $\pm 0.002^{\circ}\text{C}$ ($\pm 0.004^{\circ}\text{F}$). This apparatus yielded results within 1% of those determined at the NBS on 208-kg/m^3 (13-pcf)* fiberboard, 123-kg/m^3

* lb/ft^3 is often abbreviated in the insulation literature as pcf.

(7.7-pcf) corkboard, and three fiber glass samples of density 9.6, 15.7, and 68 kg/m³ (0.60, 0.98, and 4.25 pcf), which have k values from 33 to 52 mW m⁻¹ K⁻¹ (0.23 to 0.36 Btu in. hr⁻¹ ft⁻² °F⁻¹) for mean temperatures from 15 to 38°C (60 to 100°F). Gilbo describes a 20-cm (8-in.) GHP that used envelope-type cold plates and determined the k of 254-kg/m³ (15.9 pcf) corkboard at a mean temperature of -65°C (-86°F). He also described a 0.60-m (24-in.) GHP and k results on 138-kg/m³ (8.6-pcf) corkboard that were within ±1% of conventional methods. Woodside and Wilson authored two papers on the analysis of unbalanced edge heat losses on GHP measurements. The errors, which depend on the material's k , may be as great as 6% even though the ASTM balance requirement is satisfied. They show that the determination of two heater plate constants will allow an assessment of the unbalance error. Woodside also derived an analytical expression for the error in k due to edge heat losses and suggested a procedure for testing specimens thicker than the ASTM specifications allow if these losses are evaluated. Joy described the use of a line-heat-source method for moist insulation that showed that vapor movement can assist heat transfer. For three moist insulations he presented data that showed dramatic increases in k with water content. The insulation permeability provides some measure of the change in k to be expected. D'Eustachio analyzed hot underground pipe installations and concluded that such pipes must be protected from the deleterious effects of underground water, they must be thickly insulated to be economical, but, because of the variability of soils, the insulation conductivity is secondary to the mechanical forces and chemical reactions as a criterion for evaluating performance.

The 1966 ASTM symposium focused on the measurement of k of insulating materials for cryogenic temperatures and the need for improving these methods. This symposium included discussions of various cryogenic techniques, with three papers dealing with double-guarded cold-plate apparatuses (C 745), two with modified GHP apparatuses (C 177), two with cryogenic heat flow meters (C 518), and two with measurements using cylindrical systems. The papers dealing with the previously described ASTM standard techniques provide useful detailed information on the

technique, construction details, and performance tests. One of the cylindrical systems is an inexpensive steady-state radial heat in-flow method that measures the heat transfer rate by boiloff of a cryogenic fluid. The specimen is housed in the wall of a Dewar, which can be immersed into various cryogenic fluids, and this provides an easy method to perform parametric tests on multilayer insulations. The other cylindrical system described is a non-steady-state tester that obtains the thermal conductivity from the thermal diffusivity by measuring the rate of cooling of an insulated body, avoiding the time-consuming need of achieving thermal equilibrium throughout the specimen, and yields k values over a wide range of temperatures in one experiment. Results obtained on an alternate-layer type insulation composed of 6 μm (0.25 mil) aluminum foil separated by nonwoven fibers were within 5% of those obtained with a steady-state device.

The 1973 symposium had nearly as many papers as the total of the first three symposia and, as such, was very comprehensive, with sessions on thermal models, techniques, and results and applications. This diversity is indicated in the listing of the paper titles that follows this discussion. The contents of several of these papers have been discussed elsewhere in this report. The foregoing material clearly indicates that a great deal of effort has been devoted to the study of insulations, and present-day knowledge has been advanced greatly by the ASTM symposia.

One noteworthy shortcoming of the ASTM symposium volumes is their lack of a materials or techniques index. Consequently we have attempted to assemble such an index, and it is included at the end of this appendix. Perhaps this index will provide a useful guide to the wealth of information stored in these four volumes.

1973 ASTM Symposium Contents

Definitions and Thermal Modelling

1. What Property Do We Measure?
2. Establishing Steady-State Thermal Conditions in Flat Slab Specimens
3. Mechanisms of Heat Transfer in Permeable Insulation and Their Investigation in a Special Guarded Hot Plate
4. Water Vapor Diffusion and Frost in Porous Materials
5. Radiative Contribution to the Thermal Conductivity of Fibrous Insulations
6. Predicting Spacecraft Multilayer Insulation Performance from Heat Transfer Measurements

Techniques

7. Design Criteria for Guarded Hot Plate Apparatus
8. Suitable Steady-State Methods for Measurement of Effective Thermal Conductivity in Rigid Insulations
9. Thermal Conductance of Pipe Insulation -- A Large-Scale Test Apparatus
10. New Development in Design of Equipment for Measuring Thermal Conductivity and Heat Flow
11. Robinson Line-Heat-Source Guarded Hot Plate Apparatus
12. Calibrated Hot Box: An Effective Means for Measuring Thermal Conductance in Large Wall Sections

Results and Applications

13. Improving the Thermal Performance of the Ordinary Concrete Block
14. Some Recent Experimental Data on Glass Fiber Insulating Materials and Their Use for a Reliable Design of Insulations at Low Temperatures
15. Evacuated Load Bearing Thermal Insulation up to 800°C
16. Thermal Conductivity of Evacuated Glass Beads: Line Source Measurements in a Large Volume Bead Bed Between 225 and 300 K
17. High Performance Thermal Insulation for an Implantable Artificial Heart

18. Study of Thermophysical Properties of Constructional Materials in a Temperature Range from 10 to 400 K.
19. Analysis and Measurement of the Heat Transmission of Multi-Component Insulation Panels for Thermal Protection of Cryogenic Liquid Storage Vessels

Materials Heat-Transmission Index for ASTM Symposia

(A: 1951; B: 1957; C: 1966; D: 1973)

Aluminized mylar, C19	Gases, C114, D252
Aluminosilicate fiber	Glass fiber, C113, D40, D43, D44,
Blanket, D250	D45, D47, D231, D234, D235,
Block, D250	D236, D294
Astroquartz felt, D83	Glass fiber board, D160
Calcium silicate board, D250	Glass-wool, D160, D161
Asbestos free, D250	Gum rubber, B47
Carbon fiber, D130	HCF MOD III, D83
Cement plaster, B33	Load-bearing insulations, D251
Cork, B33	Linde SI insulation, C72
Corkboard	MX 4926, D126
7.3 pcf, A37, A40	Masonite insulating board, B33
7.7 pcf, B14	Microquartz batting, C34
8.6 pcf, B29	Microporous silica blanket, D250
13.3 pcf, A37	Min-K-2000, D277
Cork sheet, B77	Multilayer insulation, C40, C102,
Epoxy/Eccospheres R, C9	C103, C104
Evacuated glass beads, D265	Nickel-foil cups, D283
Evacuated thermal insulations —	Perlite, C116, D277
boards, blocks, blankets, D250	Pipe insulation, B83, D136
Expanded ebonite, D164	Polymethylmethacrylate, D296
Expanded perlite, D277	Polystyrene, D160
FM S131, D126	Polyurethane foam, D143
Fiberboard, B14	Evacuated, D293
Fiber-glass, B15, C50	Powders, C91
Reinforced plastic FRP, D143	Quartz, fine crushed, D165

Reinforced foam, C34	Vermiculite
Reusable surface insulation RSI, D131, D132, D78, D80	Board, D250
Rock-wool, B36, D161	Flakes, D277
Rubber board, B47	Vibracork, B22
Rubber gum, B47	Walls
Soils, B83, D165	Brick, A30
Lunar, D271	Concrete block, D219
TFE teflon, C8	Frame, A30, D206
Textolyte, D295	Windows, D208
Vacuum metal foil, D277	Doors, D209
	Wood, yellow, B33
	Zircar ZYF, D277

B-2 REFERENCES

1. *Symposium on Thermal Insulating Materials*, Am. Soc. Test. Mater. Spec. Tech. Publ. 119, American Society for Testing and Materials, Philadelphia, 1952.
2. *Symposium on Thermal Conductivity Measurements and Applications of Thermal Insulators*, Am. Soc. Test. Mater. Spec. Tech. Publ. 217, American Society for Testing and Materials, Philadelphia, 1957.
3. *Thermal Conductivity Measurements of Insulating Materials at Cryogenic Temperatures*, Am. Soc. Test. Mater. Spec. Tech. Publ. 411, American Society for Testing and Materials, Philadelphia, 1967.
4. *Heat Transmission Measurements in Thermal Insulators*, Am. Soc. Test. Mater. Spec. Tech. Publ. 544, American Society for Testing and Materials, Philadelphia, 1974.

APPENDIX C

ASTM TEST METHODS

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

APPENDIX C

ASTM Test Methods

This appendix describes the seven ASTM test methods listed in Table 5.1.

The Fourier heat conduction equation defines the thermal conductivity k as the proportionality constant between the heat current density q and the temperature gradient $\partial T/\partial x$, as

$$q = -k \partial T/\partial x . \quad (C-1)$$

Equation (C-1) and the energy-conservation principle yield partial differential equations that can be solved for various boundary conditions. It is important to realize that this definition of thermal conductivity describes a heat diffusion process that depends upon a gradient of temperature. Other equations describe heat transport phenomena such as radiation transfer, which involves surfaces and temperature differences. Indeed this definition applies to homogeneous, isotropic media and does not indicate the magnitude of k or any of the factors that may change k , such as temperature, composition, etc.

C-1 THE GUARDED HOT PLATE APPARATUS (C 177-71)

The general features of this steady-state method are shown in Fig. C-1. The apparatus consists of two identical specimen plates separated by a flat power source. The specimens are bounded on their external faces by heat sinks. The power source, usually an electrical heater plate, is so divided that the heat generated in the center portion can be precisely controlled and measured. The heat generated in the outer regions of the plate is independently controlled to provide a heat guard at the edges of the specimens. Thus, the heat that flows through the center portions of the specimens is unidirectional. Surface plates of highly conductive metal are often used between the heaters and the specimen to provide uniform temperatures at the hot faces of the specimens.

Fig. C-1. Schematic Drawing of the Guarded Hot Plate Method. From *Thermophysical Properties of Thermal Insulating Materials*, ASD-TDR-62-25 (July 1962).

The contact surfaces of all components must be as flat as possible so that interface thermal resistances are nearly uniform and localized disturbances to heat flow are practically eliminated. In operation, the components are clamped together to further reduce the thermal resistance.

Thermal conductivity, k , is calculated from:

$$k = ql/A \Delta t, \quad (C-2)$$

where q is the heat flow through one specimen, l is the specimen thickness, A is the area perpendicular to heat flow, and Δt is the temperature difference for the separation, l .

This method has been widely accepted as the standard for certain types of insulation materials. Variations of the apparatus and methods are used by investigators to meet their specific requirements.

The plates may be square or round with a central section of the heating unit of width C surrounded by a guard of specified width G , depending on the specimen thickness, l . Table C-1 shows these dimensions are in the proportion $C:G:l = 6:3:2$ to minimize heat leak effects.

Table C-1. Minimum Linear Surface Dimensions of Guarded Hot Plate

L, Maximum Specimen Thickness (mm)	Required Apparatus Dimensions, mm		
	C, Central Section	G, Width of Guard	C + 2G, Total Plate Size
33	100	50	200
50	150	75	300
75	225	113	500
100	300	150	600

As this table shows, to test 25-mm-thick (about 1-in.) specimens requires a plate that is 200 mm wide (about 8 in.), and to test specimens up to 100 mm (4 in.) thick requires a large plate, 600 mm (approximately 24 in.). Although the latter is a commonly encountered thickness among insulations, only a few such large devices exist.

The development of the guarded hot plate (GHP) is traced in a recent history of The Building Sciences Series of the National Bureau of Standards¹ (NBS). The first GHP was built in 1912 to provide coordinated and usable data pertaining to heat transmission in insulation needed for design purposes for the American Society of Refrigeration Engineers. The currently used NBS apparatus was built about 1929, and in 1945 the ASTM adopted the GHP method as a standard test method. In 1951 Robinson and Watson² completed a round-robin comparison of thermal conductivity tests on 25-mm-thick (1-in.) corkboard at mean temperatures of -7 to 50°C (20 to 130°F). The comparison involved 20 different GHPs. Figure C-2 is a frequency distribution of percentage departures of individual laboratories from the reference laboratory on the same specimens and shows a spread of -16% to +13% for the total population. If treated statistically, this corresponds to one standard deviation of 4.65%. Robinson and Watson noted that 15 of the 20 plates were within ±3% of the mean value, which implied that the C 177-45 method was capable of producing reasonably reproducible results if used with care.

Fig. C-2. Histogram of Percentage Departures of Individual Conductivity Measurements of Laboratories from those of the Reference Laboratory on the Same Specimens in the 1951 Round Robin. From Robinson and Watson;² reproduced by permission of American Society for Testing and Materials.

The NBS GHP has been used to supply measured samples of suitable insulating materials for calibration to over 300 laboratories. The currently used NBS GHP has been an invaluable tool to improving the data base of insulations; however, it is restricted in size [0.2-m-plates (8-in.)], mean temperature range -18 to 50°C (0 to 125°F), and accuracy ($\approx \pm 2\%$). The NBS is constructing a modification to the GHP described by Robinson.³ This system design uses a line source heater to diffuse heat laterally in a copper or aluminum plate. It does not produce a wholly uniform plate temperature, but it allows calculation of temperatures from only a few sensors and signifies better construction. It is hoped that this simplified 0.3-m (12-in.) plate system will obtain an accuracy better than $\pm 1\%$, will operate from -50 to 250°C (-58 to 480°F), and will eventually have vacuum capacity.

The literature contains many references concerning measurements involving forms of the GHP, each slightly different and used in different ways. Pratt⁴ notes that in practice the specifications are often abused because of lack of attention to experimental techniques, which are absolutely necessary to ensure reliable determinations. Practically, the GHP is limited to determinations on so-called homogeneous materials having a thermal conductance of less than $60 \text{ W m}^{-2} \text{ K}^{-1}$ with appropriate

thickness restrictions. However, for very thick composite building sections the guarded hot box should be used. Various GHP systems are used from 4 to 1300 K (-455 to 2370°F), and Pratt describes low-temperature plate methods, high-temperature plate methods, procedures, sample requirements, heat losses, and results obtained. The last includes a series of comparative tests initiated by the Institut International du Froid over the temperature range 273 to 313 K (32 to 100°F) on standard English fiber glass.⁴ These results were similar to the Robinson and Watson comparison but showed extreme differences of 30% for the population results. In addition, while the slopes (k vs temperature) of some curves were identical, others were very different and would indicate larger differences for any extrapolation to higher or lower temperatures.

Temperature measurement errors and unaccounted heat losses constitute the sources of error in the GHP. The former include:

1. heat flow distortion near wires of finite size,
2. thermocouple hot junction placement in air pockets or local sample inhomogeneity,
3. imprecision in the exact position of the thermocouple junctions,
4. varying thermal resistance between the samples and the plates at the positions where the thermocouples are installed.

At high temperatures these effects are magnified, and further problems are introduced by thermocouple contamination and materials incompatibility.

The essential feature of the GHP method is that one-dimensional heat flow is obtained and that there are no radial heat losses at equilibrium. Near ambient temperatures edge losses are minimal; however, away from ambient various guarding techniques are employed to control edge losses, such as use of a guard ring of specified width to sample thickness ratio (see Table C-1) and temperature control of the guard relative to the sample temperature. Various experiments on the latter effect have shown that even when the ASTM prescription is realized, differences in k of 5 to 20% are observed, depending upon the temperature and the test material.⁵ Problems of this type have reinforced the need for standard reference materials.

C-2 HEAT FLOW METER METHOD (C 518-70)

This is a steady-state but secondary method that attempts to obtain unidirectional heat flow for rapidly measuring the k of certain homogeneous insulating materials. Its calibration depends on the use of a pair of specimens whose thermal conductivity has been determined by ASTM Method C 177. For workers involved in the evaluation of a large number of materials, such as in quality control, the time factor is critical. It is mainly used for specimens having conductances less than $1.2 \text{ kW m}^{-2} \text{ K}^{-1}$ ($2.0 \text{ Btu hr}^{-1} \text{ ft}^{-2} \text{ }^{\circ}\text{F}^{-1}$), with the temperature of the specimen surfaces contacting the heat meter being in the range -45 to 540°C (-50 to 1000°F). The calibrated apparatus has a potential accuracy of $\pm 5\%$ and a reproducibility of $\pm 1.5\%$.

The general features of single and double apparatuses are shown in Fig. C-3 and include a hot plate, a heat flow meter, a sample, and a cold plate. The hot and cold plates are controlled at fixed temperatures, usually about 15 to 20 K (27 to 36°F) apart. The heat flow meter monitors the heat flowing in a central area, usually about one fourth of the total area. The heat flow meter (a thermopile) must have a sensitivity such that 1% of its output is more than $2\mu\text{V}$, and it is calibrated against two samples of a reference material. Thermocouples are used to measure the temperature drop across the specimen, ΔT_s . From a knowledge of the heat flow meter calibration, S , and its output, e_s , one calculates the test specimen k as

$$k = S e_s l_s / \Delta T_s, \quad (\text{C-3})$$

where l_s is the test specimen thickness. This method is at least 5 and perhaps 10 times faster than the GHP (C 177) and when the calibration is maintained, it can yield results within 1% of those of the slower GHP for some samples.⁴ The test specimen area and thickness requirements are the same as given in Table C-1 for the GHP method. The construction of the heat flow meter is crucial to this method and various designs are described by Pratt.⁴

Fig. C-3. Schematic Drawing of Heat Flow Meter Apparatus. Left: single-meter type. Right: double-meter type. Reproduced from 1974 *Book of ASTM Standards* by permission of The American Society for Testing and Materials.

C-3 THE GUARDED HOT BOX METHOD (C 236-66)

Both the Guarded Hot Plate and Heat Flow Meter Methods measure a quantity approximating thermal conductivity; however, for particular conditions such as large temperature differences or large thicknesses of insulation a mean k is often sought. When this " k " is divided by the thickness, one obtains the thermal conductance, C -factor. If other special conditions are imposed on the test, such as air infiltration, the property measured becomes the overall heat transmission coefficient, U -factor. The Guarded Hot Box Method is intended for measurements of C or U of various nonhomogeneous subassemblies, such as composite walls. The method is an arrangement that allows a desired steady temperature difference to be established and maintained across a test panel for a period sufficient to ensure constant heat flux and steady temperatures.

Figure C-4 depicts the general arrangement often used for the test box, guard box, test panel, and cold box, which may be constructed to allow horizontal, vertical, or tilted test conditions. The test panel is heated and cooled on opposite sides, and the temperatures are measured for each face (T_1, T_2) and air adjacent to each face (T_h, T_c). Typically the heat flow is measured as the power input to a five-sided metering box surrounded by a guard box whose temperature is controlled to achieve zero temperature differences across the meter box walls. At equilibrium the wall conductance, C , is obtained from

$$C = Q/A(T_1 - T_2) \quad (C-4)$$

The hot and cold surface conductances are calculable from the air temperatures as

$$f_1 = Q/A(T_h - T_1) \text{ and } f_2 = Q/A(T_2 - T_c) \quad (C-5)$$

so that the overall heat transmission coefficient can be evaluated from

$$\frac{1}{U} = \frac{1}{f_1} + \frac{1}{C} + \frac{1}{f_2} \quad (C-6)$$

The ASTM C 236-66 prescription contains a number of apparatus suggestions for locating and monitoring temperature sensors, controlling dew point, measuring power, etc.

As in the case of the Guarded Hot Plate Method, the National Bureau of Standards¹ played a significant role in developing and testing various guarded hot box systems before the ASTM adoption of this technique in 1954. The NBS efforts have included measuring insulating value of composite assemblies of materials in the form of walls, roofs, and floors; assessing heat transfer characteristics of about 120 walls; determination of the insulating value of reflective and nonreflective air spaces; use of a rotatable box apparatus for floor, wall, and sloped or flat ceiling orientations; comparison of fibrous and reflective insulations; and assessment of various floor slabs and wetted roof installations. Many of the results of these studies are summarized in the ASHRAE Guide.⁶

Fig. C-4. Guarded Hot Box Method Showing the General Arrangement (a), and Two Alternate Assemblies (b and c). Reproduced from Pratt⁴ by permission of Academic Press.

Pratt⁴ describes a simplified guarded hot box used at the National Physical Laboratory for tests on 0.9 by 0.9-m (36 by 36-in.) panels with one face at 195 K (-108°F). The box in this system was lined with cork and was heated internally to avoid edge losses. Mumaw⁷ has described the Owens-Corning calibrated hot box for testing panels 2.7 by 4.3 m (9 by 14 ft). The hot chamber is well insulated with urethane to minimize heat transfer to below 5% of the total energy transfer and thereby approach the maximum of 3% established for the metering box of the guarded hot box. The maximum overall error of this calibrated hot box under extreme conditions was assessed to be less than 1%. Calculated and measured thermal resistance values for seven walls with no air infiltration showed differences of $\pm 5\%$ to -7% . Recently this apparatus was used⁷ to test sound transmission loss, thermal transmittance, and rate of air leakage on full-scale specimens of typical residential exterior construction.⁸ Thermographs of two test specimens dramatically illustrate warm-side temperature variations caused by conduction through studs and through a double-hung wood window. Further application of this instrument could significantly benefit troubleshooting in insulation

installations. Comparison of calculated (ASHRAE) and measured thermal resistances for walls, doors and windows were no better than those cited above. This illustrates the problem alluded to by Pratt⁴ that "results obtained are very much dependent upon ensuring that the test sample is representative of the actual application component."

Several other guarded hot boxes are described in the open literature.⁹⁻¹² Workers in Norway⁹ have developed the capacity to test walls 1.7 by 2.2 m (67 by 87 in.) with 0.2 m (8 in.) thickness and use several well-placed heat flow meters to obtain reliable heat flow values. Data reported on walls of polystyrene foam block construction with slits show the value of sealing surface seams to reduce the apparent k . This box is intended for work on commonly used types of construction to allow calculations of heating or cooling loads and to establish quality requirements for insulation materials and workmanship. Italian workers¹⁰ have developed a system for testing 3 by 3 m (118 by 118 in.) walls in a configuration like the guarded hot plate: a central hot box with two walls, and two cold boxes. Tests on double-pane glass have shown the transmittance to increase with air velocity as $V^{0.16}$ and linearly with temperature. Their co-workers¹¹ have studied the effects of thermal oscillations on the same panels. Workers at the U.S. Department of Agriculture¹² have used a modified guarded hot box to test greenhouse materials of construction at various air velocities and in horizontal and vertical positions. They find transmittance values higher than the published ASHRAE guide values for glass.

C-4 PIPE INSULATION METHODS (C 335-69, C 691-71)

These two complementary methods involve radial heat flow techniques for homogeneous (C 335) and inhomogeneous (C 691) insulations on heated pipes. Method C 335 describes two apparatuses that use different principles to compensate for axial heat losses, the guarded ends apparatus and the calibrated end cap apparatus. This method may yield somewhat higher k values than C 177 because of factors that contribute to increasing heat losses, such as insulation clearance around the pipes and longitudinal or circumferential joints in the insulation. The guarded end apparatus is depicted in Fig. C-5 and consists of a standard steel pipe,

Fig. C-5. Guarded-End Pipe Insulation Tester. Reproduced by permission from 1974 *Book of ASTM Standards*.

not less than 0.91 m (3 ft) long, to which the insulation is applied; an electrical heater, powered by a closely regulated power supply, placed inside the pipe; means to compensate for end losses; and temperature sensors at various points of the tester. A gap is provided between the center and end sections of the heater core and the length of the end guards must be 1.5 times the test specimen thickness. The gap temperature difference must be controlled to less than 0.5% of the temperature drop through the specimen, which shall not be less than 22°C (40°F). The C 335 method suggests various positions for the temperature sensors with the specimen temperature drop being determined from the hot pipe surface temperature (T_0) and the insulation cold surface temperature (T_2). The thermal conductivity is calculated from

$$k = q \ln(r_2/r_1)/2\pi(T_0 - T_2) , \quad (C-7)$$

where r_1 and r_2 are the inner and outer radii of the pipe insulation. As constituted, this equation involves the area of the inner surface of cylindrical pipe insulation. The calibrated end cap method is very similar to this except the heat flow to or from the uncontrolled end caps is obtained from a calibration curve.

Method C 691 is very similar to C 335 except that it is for nonhomogeneous insulations, such as reflective insulations, and is intended for horizontal pipes. As described, the method yields the thermal transference (heat loss) through nonhomogeneous pipe insulation. The thermal transference (T_p) includes a thermal conductance of the insulation (C) and an outer surface heat transfer coefficient (h_2); thus

$$T_p = q/A_0(T_0 - T_a)$$

where A_0 is the insulated surface area (pipe area) and T_a is the ambient air temperature. By measurement of T_2 , one can calculate C and h_2 for the insulation. Because of the anisotropic conductive nature of the nonhomogeneous insulations, C 691 includes measurements and control of the end guards to ensure that the total axial heat flow is within $\pm 1\%$ of the heat input to the heater.

C-5 GUARDED FLAT PLATE BOILOFF CALORIMETER-FPC (C 745-73)

This flat-plate thermal conductivity apparatus includes hot and cold flat plates between which a flat sample can be installed. The ASTM C 745 prescription (see Fig. C-6) describes a double-guarded cold plate system for measuring disk samples of multilayer, powder, fiber, and cellular insulations with a k as low as $14 \text{ mW m}^{-1} \text{ K}^{-1}$ ($1 \times 10^{-4} \text{ Btu in. hr}^{-1} \text{ }^\circ\text{F}^{-1} \text{ ft}^{-2}$). The heat flow is measured in terms of the rate of boiloff of a cryogenic fluid. The sample can range in thickness from 0 to 50 mm (2 in.) with diameters up to 0.30 m (12 in.). The sample can be exposed to any desired gas at pressures from 10^{-6} torr to 1 atm (0.13 mPa to 0.1 MPa).¹³ Circulating fluids are passed through the hot plate to control its temperature at any desired value between 77 and 500 K (-320 and 440°F). Similarly, the double-guarded cold plate can be maintained between 20 and 243 K (-420 and -22°F). The sample thickness can be changed during a test by moving the hot plate, and this separation can be monitored to $25 \text{ } \mu\text{m}$ (0.001 in.). A guard shield skirt is used to control the edge temperatures of the sample to avoid heat leakages to ambient temperatures. The plate temperatures are measured at various

Fig. C-6. Cross Section of the ADL Model 12 Flat Plate Calorimeter. Reproduced by permission from the 1974 *Book of ASTM Standards*.

points with copper vs constantan thermocouples. Minimization of heat losses is critical to the technique because of the anisotropic nature and extremely low k of the multilayer evacuated insulations. The mechanical loading option is needed because k of multilayer insulation is influenced by the applied load. In addition, the k of such evacuated insulations is changed by the presence of small amounts of residual gases, so considerable time (as much as ten days) is often spent to precondition the samples before testing. The low k of these materials significantly increases the time required to establish thermal equilibrium in such a system. The overall accuracy is estimated to be $\pm 10\%$, but this does not include the contact resistance of the sample and plates.⁴

C-6 GUARDED REFRACTORY BRICK METHOD (C 201-68)

This is a steady-state absolute method for high-temperature materials. When used for measurements on insulating firebrick, a supplementary test specification (C 182-72) further describes the test. The basic apparatus, Fig. C-7, employs a 0.23 by 0.34-m (9 by 13.5-in.) specimen, either monolithic or in pieces, supported above a sectioned (for guarding)

Fig. C-7. The Guarded Refractory Brick Method. From *Thermophysical Properties of Thermal Insulating Materials*, ASD-TDR-62-215 (July 1962).

water-flow calorimeter. The specimen is unidirectionally heated by radiation and gaseous conduction from the silicon carbide diffuser slab, which is similarly heated by the silicon carbide heating elements above. The temperature drop through the specimen is sensed by thermocouples located in horizontal drilled holes near each surface and in the center of the specimen. Thus, two mean conductivity values may be calculated for each furnace control temperature from the equation

$$k = q\ell/A \Delta T , \quad (C-9)$$

where the symbols have the usual meanings.

The apparatus is normally designed for a maximum hot-face temperature of 1540°C (2800°F), but recent work¹⁴ is extending this limit to 1700°C (3100°F). The cold-face temperature is somewhat under the control of the operator and may range from near the calorimeter temperature to higher values depending upon whether an insulating spacer is placed beneath the specimen.

Round robins conducted by the ASTM C-8 committee have indicated agreements of ±5% among the various C 201 apparatuses and other test

methods.¹⁵ The method appears to have an imprecision of the same magnitude, which casts doubts on the claimed accuracy. It is subject to the same errors as the guarded hot plate or heat flow meter method, but the errors are even more troublesome because of the very high temperatures involved and the attendant experimental difficulties. In addition, a question is now being raised concerning the effect of the condition of the surface of the calorimeter plate on the measurements.

C-7 REFERENCES

1. P. R. Achenbach, *Building Research at the National Bureau of Standards Through 1968*, Build. Sci. Ser. Nat. Bur. Stand. O, U.S. National Bureau of Standards, Washington, D.C., October 1970.
2. H. E. Robinson and T. W. Watson, "Interlaboratory Comparison of Thermal Conductivity Determinations with Guarded Hot Plates," pp. 36-44 in *Symposium on Thermal Insulating Materials*, Spec. Tech. Publ. 119, American Society for Testing and Materials, Philadelphia, 1952.
3. M. H. Hahn, H. E. Robinson, and D. R. Flynn, "Robinson Line-Heat-Source Guarded Hot Plate Apparatus," pp. 167-211 in *Heat Transmission Measurements in Thermal Insulations*, Spec. Tech. Publ. 544, American Society for Testing and Materials, Philadelphia, 1974.
4. A. W. Pratt, "Chapter 6: Heat Transmission in Low Conductivity Materials," pp. 301-405 in *Thermal Conductivity*, Vol. 1, ed. by R. P. Tye, Academic Press, London, 1969.
5. Ibid, p. 355.
6. *ASHRAE Handbook of Fundamentals*, Chap. 18, p. 242, American Society of Heating, Refrigeration, and Air-Conditioning Engineers, New York, 1968.
7. J. R. Mumaw, "Calibrated Hot Box: An Effective Means for Measuring Thermal Conductance in Large Wall Sections," pp. 193-211 in *Heat Transmission Measurements in Thermal Insulations*, Spec. Tech. Publ. 544, American Society for Testing and Materials, Philadelphia, 1974.

8. H. J. Sabine et al., *Acoustical and Thermal Performance of Exterior Residential Walls, Doors, and Windows*, *Build. Sci. Ser. Nat. Bur. Stand. Ser. 77*, U.S. National Bureau of Standards, Washington, D.C., October 1970.
9. G. Lorentzen, E. Brendeng, and P. Frivik, "On the Development of Methods for Measuring Heat Leakage of Insulated Walls with Internal Convection," pp. 495-506 in *Thermal Conductivity*, *Nat. Bur. Stand. Spec. Publ. 302*, ed. by D. R. Flynn and B. A. Peavy, Jr., National Bureau of Standards, Washington, D.C., September 1968.
10. C. Codegone and V. Ferro, "Experimental Apparatus for Thermal Transmittance Measurement Through Large Size Walls," pp. 1115-1123 in *Thermal Conductivity*, ed. by C. Y. Ho and R. E. Taylor, Plenum Press, New York, 1969.
11. P. Bondi and A. Sacchi, "Experiments of Thermal Oscillations on Large Walls," pp. 1125-1139 in *Thermal Conductivity*, ed. by C. Y. Ho and R. E. Taylor, Plenum Press, New York, 1969.
12. W. A. Bailey, R. C. Liu, H. H. Klueter, and D. T. Krizek, "Measuring Heat Losses Through Common Greenhouse Covering Materials Under Different Test Conditions," pp. 941-948 in *Thermal Conductivity*, ed. by C. Y. Ho and R. E. Taylor, Plenum Press, New York, 1969.
13. P. E. Glaser et al., *Thermal Insulation Systems, A Survey*, *NASA Spec. Publ. 5027*, National Aeronautics and Space Administration, Washington, D.C., 1967.
14. C. Semler, Refractories Research Center, Columbus, Ohio, private communication, December 1975.
15. W. C. Bohling, Babcock and Wilcox Company, Augusta, Georgia, private communication, December 1975.

APPENDIX D

ASTM THERMAL CONDUCTIVITY EQUIPMENT AND STANDARDS SURVEY

**THIS PAGE
WAS INTENTIONALLY
LEFT BLANK**

APPENDIX D

ASTM Thermal Conductivity Equipment and Standards Survey

In 1971, the Thermal Conductance Subcommittee C-16.30 of ASTM C-16 Committee on Thermal and Cryogenic Insulating Materials initiated a survey covering the users of thermal conductivity equipment in the United States and abroad. The computer-printed results of the survey are reproduced at the end of this appendix, preceded by a rearrangement of the results prepared by the authors of this report. We understand that this survey is presently being updated and will be reissued. Additionally, we must emphasize that while the survey essentially covered the free world, our discussion is restricted to the U.S.A. only.

The focal point of the survey was reference materials of low thermal conductivity for possible use as standards. Germane to this question, however, are the types, sizes, and characteristics of the existing apparatus that might be used for the qualifying measurements on the particular selected materials. Also, the selection of materials for reference standards requires knowledge of the needs of the measurer. Accordingly, this survey produced a listing of measuring equipment that represents a majority of the total population and shows the diversity of size and type.

In his letter of transmittal of the survey, C. M. Pelanne* comments, "The reason for the long delay in developing reference standards is made obvious in this survey. No clear course appears from these data. A solution to this problem will require the cooperation of the participants in the survey and the ASTM Subcommittees involved in the related fields." Reasons for this statement are many. For instance, the survey was initiated in late 1971, responses were collected through September 1973, and the tabulation was released in September 1974. In addition, 40% of the replies suggested alternate or additional materials, but only 50% of those replying would be willing to purchase samples. The previously mentioned wide diversity in size, type, and temperature ranges for the apparatus population obviously makes the selection of standard materials exceedingly difficult.

*Johns-Manville, Denver, Colorado.

Some interesting observations can be made concerning the respondents to the survey. Of the 123+ pieces of thermal conductivity equipment reported in the U.S.A., more than 25% are located within one company, Johns-Manville. Another 25% are within four companies: two insulation manufacturers, and two aerospace firms. The remaining half are scattered among some 32 other sites. Of the 37 respondents, 15 could be classified as universities or research centers and the remainder as manufacturers or suppliers of insulations. Thus, while equipment is moderately concentrated, measurement capacity is to some extent broadly distributed. Also significant is the observation that, for whatever reason, the ASTM survey has some serious omissions. For example, the Refractories Research Center at Ohio State University operates two C 201 Refractory Testers that are not reflected in the survey. Several other refractory manufacturers have measurement capabilities that also are not listed. The authors are aware of other equipment in industry or government-operated laboratories such as their own that is not cited. These observations are not intended as any negative reflection on the ASTM survey, but rather to illustrate how difficult it is to completely survey any area. Nonetheless, the ASTM survey provides a valuable compilation that to the authors' knowledge is unique.

Concerning the types of equipment, the survey indicates that guarded hot plates (C 177) account for about 33% of the total number, while heat flow meters (C 518) constitute about 25%. The remaining devices include a very few guarded or unguarded hot boxes (C 236), pipe insulation testers (C 335), refractory testers (C 201), guarded plate calorimeters (C 745), various probes, and a wide variety of other types of apparatus.

Since thermal insulations are in general rather inhomogeneous on a fine scale, necessitating a large sample, the size of an apparatus is of great interest. Only four guarded hot plates (GHP) can accommodate samples up to 0.1 m (4 in.) thick. None can measure on thicker samples. Three heat flow meter (HFM) devices are theoretically large enough to accommodate a 0.15-m-thick (6-in.) sample. Most apparatuses are suitable for thicknesses only up to 25 mm (1 in.). Some workers in this field have stated, "There is no rationale in making measurements on thin samples

when the materials are used only in thick sections." The survey reveals, then, that only a very few apparatuses are available for testing thick samples. For very large samples or for composites containing more than one material, such as a wall section, only four apparatuses appeared in the survey, and these operate only near ambient temperatures. None are available for high-temperature testing.

With regard to operating temperature, there is a tremendous variation in the reported equipment from liquid-helium temperatures to 3000°C (5432°F). Of the 81 GHPs and HFMs, 19 are capable of cryogenic temperatures. Eight apparatuses of other types have the same low-temperature capacity. Obviously nearly all equipment can operate near ambient temperature, but only 19 GHP and HFM apparatuses will obtain hot-face temperatures above 600°C (1112°F). The same is true for only 10 of the 42 other apparatuses.

Statements related to precision and accuracy are difficult to make or to interpret, but the survey did address this area. One must assume that the answers provided were for the optimum situation since they are, in general, better than those having been demonstrated by round-robins, wherein data spreads exceeded $\pm 12\%$. The vast majority of users of GHPs claim 5% accuracy and 2% precision, though some give accuracies as low as 1%. It is interesting to note that stated accuracies of some HFMs equal or exceed that of GHPs used for their calibration, a situation that clearly cannot be obtained with a transfer standard. Little can be said concerning the other types of apparatuses since they are so diverse. The ASTM C-16 Committee obviously recognizes the difficulties involved in assessing accuracy and precision since the primary interest of the survey was to select reference materials of low thermal conductivity to be used as standards. Only through the use of recognized reference materials may the various apparatuses and operators be qualified, errors recognized and corrected, and order evolve from the chaos.

In summary, this ASTM survey has provided much valuable information heretofore not readily available. It is, however, unfortunate that a significant number of apparatuses are not included in the survey. We recommend that a second effort be directed toward filling these voids and that the results be widely distributed. Further, the quest for and development of reference materials must be given a high priority.

Authors Rearrangement of ASTM Survey

Company and Apparatus	Sample Dimensions, in. ^a		Temperature, °F ^a		Accuracy (%)	Precision (%)
	Extent	Thickness	Minimum Cold Face	Maximum Hot Face		
Armstrong Cork Company Lancaster, Pennsylvania						
1 Guarded hot plate	8 × 8	1 1/3	-112	140	1	1
1 Guarded hot plate	24 × 24	4	20	140	1	1
1 Heat flow meter	8 × 8	1 1/3	20	140		1
1 Thin heater device	6 × 12	1/4			3	
1 Thin heater device	10 × 12	1	-320	500		
Avco Systems Lowell, Massachusetts						
4 Guarded hot plates	4.5 × 4.5	1		1830	3	5
1 Guarded radial (unspecified)						
Babcock & Wilcox Alliance, Ohio						
1 Pipe tester (3 in.)			70	1470	8	3
Bendix Corporation Kansas City, Missouri						
1 Guarded hot plate	8 diam	1 1/4	-310	1800	5	2
Carborundum Company Niagara Falls, New York						
1 Guarded hot plate	12 diam	1	70	2200		5
University of Dayton Dayton, Ohio						
1 Cylindrical (unspecified)			-450	85		
Dow Chemical Company Midland, Michigan						
1 Guarded hot plate	8 diam	1 1/3	-330	500	5	
1 Guarded hot plate	10 × 10	1 1/2		1200	5	
1 Heat flow meter	8 × 8	4			5	
1 Radial (unspecified)						
Dynatech Cambridge, Massachusetts						
2 Guarded hot plates	8 diam	1 1/3	-290	1830	5	2
1 Guarded hot plate	24 × 24	4	-290	480	3	2
1 Heat flow meter	12 × 12	2	-5	430	3	1
1 Heat flow meter	12 × 12	2	32	212	4	1
General Electric Philadelphia, Pennsylvania						
1 Guarded hot plate	8 diam	1	-780	1880	10	2
1 Thermal comparator (unspecified)						
B. F. Goodrich Sponge Products Shelton, Connecticut						
1 Thermal comparator	6 × 6	3	50	100	2	1
ICI American, Inc. Wilmington, Delaware						
1 Probe	4 × 6	12	75		3	1/2
1 Modified hot plate	6 × 6	1/2	32	125	3	1/2
Johns-Manville Denver, Colorado						
1 Guarded hot plate	12 × 12	1 1/2	50	500	5	2
2 Guarded hot plates	18 × 12	4	50	500	5	2
1 Guarded hot plate	24 × 12	4	50	500	5	2
1 Guarded hot plate	24 × 12	2 1/2	50	500	5	2
2 Guarded hot plates	10 diam	1	100	1100	5	2
1 Guarded hot plate	8 diam	1	100	1000	5	2
1 Guarded hot plate	4 × 12	1/2	50	212	5	2
12 Heat flow meters	12 × 12	2	50	100	5	1
1 Heat flow meter	12 × 12	1	220	480	5	1
1 Heat flow meter	12 × 12	1	220	780	5	2
1 Heat flow meter	12 × 12	1	-280	80	5	2
1 Heat flow meter	12 × 12	1	550	1292	5	2
2 Heat flow meters	36 × 12	6	50	100		
1 C 201 Refractory tester	13 × 16	3	100	2400		
1 Guarded hot box	65 × 80	10	32	140		
4 Pipe testers (2, 3, 4, and 5 in.)			75	1200		

Authors Rearrangement of ASTM Survey (Continued)

Company and Apparatus	Sample Dimensions, in.		Temperature, °F		Accuracy (%)	Precision (%)
	Extent	Thickness	Minimum Cold Face	Maximum Hot Face		
University of Kentucky Lexington, Kentucky						
1 Line source for powders	1 diam	1/2		625	10	
R. M. Lander Minneapolis, Minnesota						
1 Guarded hot plate	12 x 12	1 1/2	-100	240	2	1
1 Pipe tester (unspecified)						
Lawrence Livermore Laboratories Livermore, California						
1 Special unguarded hot plate	4 diam	1/2	-75	1300	2	
A. D. Little Cambridge, Massachusetts						
1 Guarded hot plate	12 diam	1	-450	265	5	2
1 Probe (unspecified)			-450	265		
Lockheed Missiles and Space Center Palo Alto, California						
1 Guarded hot plate	7 diam			3600		
1 Guarded hot plate	8 diam			930		
1 Heat flow meter	8 diam					
1 Flat plate calorimeter	16 diam			930		
1 Flat plate calorimeter	24 diam			212		
2 NBS-type cryostats	5 diam			212		
Martin Marietta Denver, Colorado						
1 Guarded hot plate	8 diam	1 1/4	-310	1800		5
McDonnell Douglas Corporation St. Louis, Missouri						
1 Guarded hot plate	10 diam	1 1/4	80	2200	5	2
1 Guarded hot plate	12 x 12	1 1/4	50	590	5	2
1 Guarded hot plate	14 diam	2	-320	480	5	
1 Thermal comparator	3 diam	2	50	2200	15	
1 Guarded cold plate calorimeter	20 diam	2	-450	230	5	
1 Radial flow calorimeter	32 long	6 diam	-320	230		
1 Tank calorimeter, spherical	18 diam	1	-450	185		
1 Pulsed thermal comparator	0.2	0.04	75	75	20	5
Mobay Chemical Company Pittsburgh, Pennsylvania						
1 Heat flow meter	14 x 14	2 1/2	40	110	3	3
National Bureau of Standards Boulder, Colorado						
Plan to build GHP	3 diam		-454	1350	10	2
National Bureau of Standards Washington						
1 Guarded hot plate	8 x 8	1 1/3	-20	150	1	1/2
National Gypsum Company Buffalo, New York						
1 Guarded hot plate (unspecified)	12 x 12	1 1/2	-30	100		
1 Heat flow meter						
North American Rockwell Downey, California						
1 Guarded hot plate	8 diam	1 1/3	-320	2200		5
1 Cold plate apparatus	13 diam	2	80	1000		5
1 Envelope-type cold plate	6 x 6	1	-320	200		5
Owens-Corning Fiberglass Granville, Ohio						
4 Guarded hot plates	16 x 16	3	-320	980	1	
Many heat flow meters	14 x 14	3	55	95		
1 Heat flow meter	36 x 36	6	55	95		
1 Guarded hot box	53 x 72		32	150		
1 Calibrated hot box	108 x 168	12	-50	150		
1 3-in. Pipe tester	36 long		70	1100		

Authors Rearrangement of ASTM Survey (Continued)

Company and Apparatus	Sample Dimensions, in.		Temperature, °F		Accuracy (%)	Precision (%)
	Extent	Thickness	Minimum Cold Face	Maximum Hot Face		
Pittsburgh-Corning Pittsburgh, Pennsylvania						
1 Guarded hot plate	8 diam	1 1/3	14	1800	5	
1 Heat flow meter	12 x 12	2	14	875	7	
2 Heat flow meters	4 x 4	1	14	200	5	3
PPG Industries Springdale, Pennsylvania						
1 Heat flow meter	12 x 12	2	14	450	5	
Reynolds Aluminum Richmond, Virginia						
1 Guarded hot box	24 x 48	4	10	80		
South Dakota School of Mines Rapid City, South Dakota						
1 Guarded hot plate	4 x 4	1/2	-330	260	5	2
1 Radial heat flow (?)	15 long	1 diam	-330	260	5	2
Southern Research Birmingham, Alabama						
1 Guarded hot plate	14 x 14	3	-320	1000	5	3
1 Guarded hot plate	3.25 diam	1/2	-320	1000	5	3
1 Guarded hot plate	7 diam	1	300	1000	5	3
1 Radial heat flow			1490	5430	10	
TPRC Purdue West Lafayette, Indiana						
1 Guarded hot plate (unspecified)						
1 Thermal comparator (unspecified)						
U.S. Army CRREL Hanover, New Hampshire						
1 Guarded hot plate	20 x 20	3	-60	240	3	
1 Probe	8 long	3 diam	-60	212	5	2
1 Probe (unspecified)						
U.S. Army Natick Laboratories Natick, Massachusetts						
1 Guarded hot plate	6.5 diam	1	-330	260	2	1/2

*Dimensions in inches may be converted to meters by multiplying by 0.0254. Temperatures in °F may be converted to °C by subtracting 32, then multiplying by 5/9.

ASTM THERMAL CONDUCTIVITY EQUIPMENT AND STANDARDS SURVEY

SEPT 1973

 * INDEX *

	PAGE
SUMMARY OF SURVEY	
LIST OF EQUIPMENT TOTALS	-1 -1
SIZE AND TEMPERATURE RANGES	-1 -1
REFERENCE MATERIAL QUESTIONS	-1 -2
MAXIMUM OPERATING TEMPERATURES	-1 -2
DISTRIBUTION OF EQUIPMENT SIZES	-1 -3
TABULATION OF SURVEY DATA	
UNITED STATES	-2 -1 TO -5
FOREIGN	-3 -1 TO -3
CODING SYSTEM	
LISTING	-4 -1 TO -3
EXAMPLE OF CODING SYSTEM	-4 -4 TO -6
BACKGROUND INFORMATION - QUESTIONNAIRE	-5 -1 TO -5

ANY SUGGESTIONS, ADDITIONS, CORRECTIONS OR COMMENTS PERTAINING TO THIS LISTING
 SHOULD BE ADDRESSED TO-

R P TYF
 ASTM C-16.30, CHAIRMAN
 DYNATECH R/D
 99 FRIE STREET
 CAMBRIDGE MASS 02139

OR

C M PELANNE
 ASTM C-16.30, MEMBER
 JOHNS MANVILLE CORP
 RESEARCH AND DEVELOPMENT CENTER
 P O BOX 5108
 DENVER COLORADO 80217

ASTM THERMAL CONDUCTIVITY EQUIPMENT AND STANDARDS SURVEY

SEPT 1973

PAGE -1 -1

 * SUMMARY OF SURVEY *

TABLE 1 - LIST OF EQUIPMENT

COUNTRY	ID NUMBER		EQUIPMENT						
	NO	OF	GUA	HOT	PLATE	HEAT	HOT		
		ANSWER	SQUARE	ROUND	METERS	BOXES	PIPES	PROBE	OTHER
UNITED STATES	01	37	22	26	33+	4	8	5	25
CANADA	02	5	7	1	3+			2	2
DENMARK	12	1	1	1					
FINLAND	13	1	2		2				3
FRANCE	14	4	2	1	3	1			
ITALY	15	3	3	1	1				
NORWAY	16	1	2			1			
SWEDEN	17	2		1	1				
UNITED KINGDOM	18	5	2	2	1				2
NETHERLANDS	19	2	3		3				2
GERMANY	41	1							
JAPAN	21	1		1	1		1		
AUSTRALIA	31	1	1					1	
NEW ZEALAND	32	1	1						
TOTAL	--	65	46	34	48+	6	9	8	34

TABLE 2 - SIZE AND TEMPERATURE RANGES

	NUMBER OF PIECES	SIZE MM MIN	MAX	THICKN MM MIN	MAX	TEMPERATURE LIMITS DEGC HIGH	LOW
**** GUARDED HOT PLATES SQUARE							
UNITED STATES	22	100	610	12	102	650	-200
FOREIGN	24	25	1000	34	150	1000	-170
**** GUARDED HOT PLATES CIRCULAR							
UNITED STATES	26	70	356	12	50	2000	-277
FOREIGN	8	200	340	25	70	1400	-190
**** HEAT METERS							
UNITED STATES	33+	100	914	25	152	700	-173
FOREIGN	15+	203	600	25	100	500	-100
**** OTHER EQUIPMENT							
UNITED STATES	42	5	4267	1	305	3000	-270
FOREIGN	15	10	2200	2	305	1600	-180

ASTM THERMAL CONDUCTIVITY EQUIPMENT AND STANDARDS SURVEY

SEPT 1973

PAGE -1 -2

SUMMARY OF SURVEY (CONT)

TABLE 3 - ANSWERS TO REFERENCE MATERIAL QUESTIONS

WILLING TO PARTICIPATE IN MEASUREMENTS

X

	YES	MAYBE	NO	
UNITED STATES	28	6	3	
FOREIGN	21		7	
TOTAL	49	6	10	76 PCT YES

WILLING TO BUY SAMPLES

X

	YES	MAYBE	NO	
UNITED STATES	18	18	1	
FOREIGN	14	18	5	
TOTAL	32	27	6	49 PCT YES

SUGGESTS OTHER MATERIALS FOR STANDARDS SEE COMMENT CARD -3

X

	YFS	MAYRE	NO
UNITED STATES	15		22
FOREIGN	3		25
TOTAL	18		47

● 政 府 在 經 濟 發 展 中 的 作 用

TABLE 4 - DISTRIBUTION OF MAXIMUM OPERATING TEMPERATURES

TEMPERATURES											1	1	1	1	1	1	1	1	1	2	
DEG C (TIMES 100)	0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9	0

***** GUARDED HOT PLATES SQUARE

UNITED STATES	3	4	6	1	5	1		
FOREIGN	12	2	4	2	1	1	1	1

***** GUARDED HOT PLATES CIRCULAR

UNITED STATES		2	3		3	2	1		2	7	1	3					1
FOREIGN		2			1		1	1	1		1				1		

***** HEAT METERS

UNITED STATES	24	1	3	3	1
FOREIGN	8		5	1	

ASTM THERMAL CONDUCTIVITY EQUIPMENT AND STANDARDS SURVEY

SEPT 1973

PAGE -1 -3

SUMMARY OF SURVEY (CONT)

FIG 1 - DISTRIBUTION OF EQUIPMENT SIZES

NUMBER

(1)

UNITS

25

24

23

22

21

20

19

18

17

16

15

14

13

12

11

10

9

8

7

6

5

4

3

2

1

X UNITED STATES
O FOREIGN

1 2 3 4 5 6 7 8 9 1
MM X 100 0

GUARDED HOT PLATES
SQUARE

1 2 3 4 5 6 7 8 9 1
MM X 100 0

GUARDED HOT PLATES
CIRCULAR

1 2 3 4 5 6 7 8 9 1
MM X 100 0

HEAT METERS

***** END *****

ASTM THERMAL CONDUCTIVITY EQUIPMENT AND STANDARDS SURVEY

SEPT 1973

PAGE -2 -1

***** UNITED STATES *****

CODE	ORGANIZATION	TOWN	STATE	NAME	STD
KEYS					

1010101	REYNOLDS ALUMINUM	RICHMOND VA		BURLEY	123
1010202	SOUTH DAKOTA SCHOOL OF MINES	RAPID CITY SD		ASHWORTH	121
1010306	OWENS-CORNING FIBERGLAS	GRANVILLE OHIO		HOLLINGSWORTH	111
1010401	MARTIN MARIETTA	DENVER COL		FARMER	113
1010502	A.D.LITTLE	CAMBRIDGE MASS		WECHSLER	121
1010602	NATIONAL GYPSUM CO	BUFFALO NY		VOLK	113
1010704	THE DOW CHEMICAL CO	MIDLAND MICH		GLEASON	111
1010803	PITTSBURG CORNING	PITTSBURG PA		R GERRISH	221
1010901	THE BENDIX CORPORATION	KANSAS CITY MO		BESHONER	113
1011002	R M LANDER	MINNEAPOLIS MINN		LANDER	223
1011108	MCDONNELL DOUGLAS CORP	SAINT LOUIS MO		MCCRARY	113
1011202	USA CRREL	HANOVER NH		KAPLAR	221
1011301	USA CRREL	HANOVER NH		MCGAW	121
1011401	THE CARBORUNDUM COMPANY	NIAGARA FALLS NY		LABAU	111
1011501	US ARMY NATICK LABORATORIES	NATICK MASS		HOGG	223
1011607	ARMSTRONG CORK CO	LANCASTER PA		ZABAWSKY	123
1011706	LOCKHEED M.S.C.	PALO ALTO CAL		CUNNINGTON	123
1011801	NRS - BOULDER	BOULDER COL		ARNETT	123
1011903	THERMOPHYSICAL RES PURDUE	WEST LAFAYETTE IND		TAYLOR	323
1012001	UNIV. OF KENTUCKY			CREMERS	221
1012101	BABCOCK & WILCOX CO	ALLIANCE OHIO		WELCH	123
1012204	SOUTHERN RESEARCH	BIRMINGHAM ALA		ENGLEKE	113
1012317	JOHNS-MANVILLE	DENVER COL		PELANNE	123
1012401	UNIVERSITY OF DAYTON	DAYTON OHIO		KREITMAN	221
1012500	NRS BOULDER	BOULDER COL		LUDTKF	321
1012601	P P G INDUSTRIES	SPRINGDALE PA		WEISSMANN	113
1012701	MORAY CHEMICAL CO.	PITTSBURGH PA		BARTELS	113
1012801	LAWRENCE LIVERMORE LABS.	LIVERMORE CAL		CORNELL	113
1012901	R.F.GOODRICH SPONGE PRODUCTS	SHELTON CONN.		DOBAY	123
1013004	DYNATECH	CAMBRIDGE MASS.		TYE	113
1013101	NATIONAL BUREAU OF STANDARDS	WASHINGTON D.C.		WATSON	111
1013202	I C I AMERICAN INC.	WILMINGTON DEL.		FLINT	113
1013302	DOW CHEMICAL CO.	MIDLAND MICH.		DIBERT	111
1013402	AVCO SYSTEMS	LOWELL MASS.		CROWLEY	111
1013500	JANESVILLE PRODUCTS	NORWALK OHIO		KOUPAL	333
1013602	GENERAL ELECTRIC CO. RESD	PHILADELPHIA PA.		BRAZEL	111
1013703	NORTH AMERICAN ROCKWELL	DOWNY CAL.		ALLEN	113

ASTM THERMAL CONDUCTIVITY EQUIPMENT AND STANDARDS SURVEY SEPT 1973
 PAGE -2 -2

***** UNITED STATES *****

CODE ENTR EQUIPM. ---- SIZE --- * ---- TEMP --- * --MEASUREMENTS- --- C
 LONG WIDE TKN HOT- COLD DIF
 KEYS

***** GUARDED HOT PLATES SQUARE

2010202	0101	112	121	100	100	12	125	-200		11	22	7	11	50	20	1
2010306	0104	1121141	406	406	76	530	-194			11	22	5	1	10		1
2010602	0101	11														
2010704	0201	11	2122	254	254	38	650			11	3	1	1	50		
2011002	0101	1121121	300	300	38	115	-75	50		11	22	4	11	20	01	
2011108	0201	1121122	305	305	32	310	10			11	22	1	1	50	20	
2011202	0101	1122122	500	500	76	115	-50	5	2	1	22	4		30		1
2011607	0101	1121	22	203	203	34	60	-80		11	22	1	1	10	10	
2011607	0201	1121	22	610	610	102	60	-7		11	22	1	1	10	10	
2011903	0101	1	122				25									
2012204	0101	11	2142	356	356	76	530	-194		11	3	4	2	50	30	1
2012317	0101	1123121	300	300	38	260	10	250	1	11	22	5	1	50	20	
2012317	0202	1121121	460	460	54	260	10	250	1	11	22	5	1	50	20	
2012317	0301	1121121	610	610	100	260	10	250	1	11	22	5	1	50	20	
2012317	0401	1133121	610	610	63	260	10	250	1	11	22	5	1	50	20	
2012317	0701	1133141	100	100	12	100	10	90	1	11	22	5	1		20	
2013004	0201	1142122	600	600	100	250	-180			13	22	5	1	1	30	20
2013101	0101	1121122	203	203	33	66	-29			11	22	4	1	10	05	1

***** GUARDED HOT PLATES CIRCULAR

2010401	0101	1222161	204		32	1000	-190			11	22	4	2		50	
2010502	0101	12	2162	300		25	130	-270		1	3	4	1	50	20	1
2010704	0101	12	2142	203		33	260	-200		11	3	1	1	50		1
2010803	0101	1222122	203		33	980	-10			1		5	1	50		
2010901	0101	1222141	203		32	980	-190			11	22	4	1	1	50	20
2011108	0101	1222142	254		32	1200	27			11	13	1	1	50	20	
2011108	0301	1221141	356		50	250	-195			11	22		1	50		
2011401	0101	1222162	303		25	1200	20	580	1	1	11	2	101		50	1
2011501	0101	1212161	165		25	125	-200	50	1	14	22	4	2	20	5	
2011706	0101	12	2141	178		2000		700	1	11			2			
2011706	0201	12	2141	203		500				11			2			
2011801	0101	12	252	76		730	-277			11	22			100	20	1
2012204	0201	12	2142	83		12	530	-195		11	3	4	2	50	30	
2012204	0301	12	2142	187		25	530	-194		11	3	4	2	50	30	
2012317	0502	1222121	250		25	600	40	110		11	22	1	1	50	20	
2012317	0601	1222141	200		25	1100	90	110		11	22	1	1	50	20	
2013004	0102	1222152	200		33	1000	-180			13	22	5	1	1	20	50
2013302	0101	1242122	203		33	260	-195			14	3	1	2	20	10	1
2013402	0104	1243162	117		25	1000		90	1	1	23	5	1	1	50	50
2013602	0101	1222141	200		25	1030	-173	500		14	23	5	111	100	20	1
2013703	0101	1222142	203		33	1200	-196	999	1	1	22	5	111		50	1

ASTM THERMAL CONDUCTIVITY EQUIPMENT AND STANDARDS SURVEY

SEPT 1973

PAGE -2 -3

***** UNITED STATES *****

CODE ENTR EQUIPM. *--- SIZE ---* *--- TEMP ---* *--- MEASUREMENTS ---* C
 LONG WIDE TKN HOT- COLD DIF

KEYS

***** HEAT METERS

2010306	0299	2121121	356	356	76	35	13	22	11	5	2		1
2010306	0301	2113122	914	914	152	35	13	22	11	5	2		
2010602	0201	21 2121	300	300	38	38	-	35	12	4	2		
2010704	0301	21 2122	203	203	104				11	3	1	2	50
2010803	0201	2112122	300	300	50	470	-	10	1	5	2		70
2010803	0302	2141122	100	100	25	90	-	10	28	1	5	2	50 30
2011607	0301	2111 2	203	203	34	60	-	7			2		10
2011706	0301	22 2141	203						11		2		
2012317	0810	2112122	300	300	50	38	10	28	12	6	2		50 10
2012317	0902	2113141	300	300	50	38	10	28	11	5	2		50 10
2012317	1001	2112122	300	300	25	250	105	145	11	5	2		50 20
2012317	1101	2112122	300	300	25	416	105	310	11	5	2		50 20
2012317	1201	2112121	300	300	25	27	-173	200	11	5	2		50 20
2012317	1301	2112121	300	300	25	700	288	412	1 11	5	2		50 20
2012317	1702	2112121	914	914	150	38	10		12	6	2		1
2012601	0101	2112221	305	305	50	230	-	10	1	3	4	2	50
2012701	0101	2142122	356	356	63	43	4	28	11	3	4	2	30 30
2013004	0301	2112222	300	300	50	220	-	20	13	4	2	1	30 10
2013004	0401	2112222	300	300	50	100	0		14		2	1	40 10 1
2013302	0201	2142122	305	305	100	38	10	28	14	3	1	2	20 20

ASTM THERMAL CONDUCTIVITY EQUIPMENT AND STANDARDS SURVEY

SEPT 1973

PAGE -2 -4

***** UNITED STATES *****

CODE ENTR EQUIPM. ---- SIZE --* ---- TEMP ----- *-MEASUREMENTS----- C
 LONG WIDE TKN HOT- COLD DIF

KEYS

**** OTHER EQUIPMENT

2010101	0101	3311121	610	1220	100	27	-12	39	11	12	4	2		
2010202	0201	941	161	380		38	125	-200	5	11	22	7	11	50 20
2010306	0401	3313121	1854	1346			65	-0		11	11	1	1	
2010306	0501	4311121	4267	2743	305		65	-45		11	11	1	1	
2010306	0601	54	1121	914		76	600	23		11	22	1	1	
2010502	0201	6					130	-270						
2010704	0401	94												
2011002	0201	5												
2011108	0401	9212142	76		50	1200	10		11		200	150		1
2011108	0501	9212142	521		50	110	-270		11	22	1	50		1
2011108	0601	9111111	825		152	110	-195		11		1			1
2011108	0701	961	111	457		25	85	-270	11					1
2011108	0801	9213	22	5		1	20				2	200	50	1
2011202	0201	6												
2011301	0101	641	121	203	76	38	100	-50		14	3	21	50	20
2011607	0401	932	22	102	152	6			11	23	1	30		1
2011607	0501	932	22	254	305	25			11	23	1	30		1
2011607	0601	6					260	-195	1					
2011607	0701	54												
2011706	0401	92	2141	406			500		11	2	1			1
2011706	0501	92	2141	610			100		11	2	1			1
2011706	0601	94	1141	140			100		11					1
2011903	0301	9	122											1
2012001	0101	951	151	25	12		330			3	2	100		1
2012121	0101	5413121	76				800	20	999	1	11	22	1	1 80 30
2012204	0401	94	162		8	3000	810		11	3	4	1	1 100	1
2012317	1401	9312121	400	330	76	1300	40		11	3	1	1		1
2012317	1501	3313121	2030	1650	250	60	0	60	1	11	11	1	1	
2012317	1604	54	2121			630	20	600	1	11	13	1		1
2012401	0101	94	25		10	30	-270		4	13				1
2012801	0101	9223152	102		12	700	-60		11	23	1	211	20	1
2012901	0101	9112122	152	152	76	38	10		1	7	2		20	10 1
2013202	0101	6312121	102	102	305	23			11	3	3		30	05 1
2013202	0201	9121122	152	152	12	50	0	50	11	3	3		30	15 1
2013402	0201	9												1
2013602	0201	91121												1
2013703	0201	9142142	330	330	50	537	27		1	3	5	11		50 1
2013703	0301	9343141	153	150	25	93	-196		1	22	5	11		50 1

ASTM THERMAL CONDUCTIVITY EQUIPMENT AND STANDARDS SURVEY

SEPT 1973

PAGE -2 -5

***** UNITED STATES *****

***** COMMENT CARDS *****

KEYS

***** EQUIPMENT COMMENTS *****

3010306 02 UNDEFINED NUMB OF HM BUT MANY
 3011108 04 THERMAL COMPARATOR
 3011108 05 GUARDED COLD PLATE CALORIMETER
 3011108 06 RADIAL FLOW CALORIMETER
 3011108 07 TANK CALORIMETER
 3011108 08 PULSED THERMAL COMPARATOR
 3011607 04 THIN HEATER K APPARATUS
 3011607 05 THIN HEATER K APPARATUS
 3011706 04 16 IN FLAT PLATE CALORIMETER
 3011706 05 24 IN FLAT PLATE APPARATUS
 3011706 06 4 IN NRS TYPE CRYOSTATS
 3011801 01 NO APP AT THIS TIME - PLAN TO BUILD
 3011903 03 THERMAL COMPARATOR
 3012001 01 LINE SOURCE FOR POWDERS
 3012104 04 RADIAL INFLO
 3012317 14 C 201 WATER CALORIMETER
 3012317 16 CALIBRATED END PIPE TESTERS 2,3,4 AND 5 INCH DIAM.
 3012317 17 36 IN HEAT METERS BEING BUILT
 3012401 01 MAYBE RADIAL HEAT FLOW APP (2 COMMENT CARDS)
 3012801 01 SPECIAL UNGUARDED HOT PLATE
 3012901 01 COMPARATOR
 3013004 04 ELECTRONIC CALCUL DIGITAL READOUT OF K
 3013202 01 PROBE ASTM D2726
 3013202 02 DUPONT MODIFIED HOT PLATE
 3013402 02 GUARDED RADIAL OUTFLOW TEST APPARATUS (2 COMMENT CARDS)
 3013602 02 DYNATECH TC 1000 COMPARATOR (2 COMMENT CARDS)
 3013703 01 DYNATECH TCFGM (3 COMMENT CARDS)
 3013703 02 AIR COOLED COLD PLATE APP. (NR/SD BUILT) (3 COMMENT CARDS)
 3013703 03 ENVELOPE - TYPE COLD PLATE - BANJO - (NR/SD BUILT) (3 COMMENT CARDS)

***** REFERENCE MATERIALS *****

3010202 01 REF MAT NYLON BELOW -150C
 3010306 01 REF MAT SEE LETTER
 3010502 01 REF MAT GLASS BEADS
 3010704 01 REF MAT STYROFOAM HD-300 CURED ALSO DOW CERAMIC FOAM
 3011202 01 REF MAT FOAMED POLYSTYRENE AND POLYURETHANE
 3011401 01 REF MAT ALUMINO SILICATE FIBER BELOW 900C
 3012104 01 REF MAT PYREX 7740 - PLEXIGLASS - TEFLON
 3012401 01 NYLON CRYOGENICS (2COMMENT CARDS)
 3013101 01 GUM RUBBER
 3013302 01 STYROFOAM HD -2
 3013402 01 PYROLYZED PLASTIC-POROUS SILICA -STAINLESS STEEL FELT (2 COM. CARDS)
 3013602 01 R.E.I.FIBROUS CERAMIC RIGID S.A.M. FIBROUS SILICA (2 COM. CARDS)

***** UNITED STATES *****

***** END *****

ASTM THERMAL CONDUCTIVITY EQUIPMENT AND STANDARDS SURVEY

SEPT 1973

PAGE -3 -1

***** FOREIGN COUNTRIES *****

CODE	ORGANIZATION	TOWN	COUNTRY	NAME	STD
KFYS					

1150101	POLITECNICO DI TORINO NUCLEARI	TORINO IT.			123
1150202	ISTITUTO DI FISICA TECNICA	PADOVA IT.		DE PONTE	113
1130304	INSTITUTE TECHNICAL RESEARCH	HELSINKI FIN.		SIITONEN	113
1160403	UNIVERSITETET I TRONDHEIM	TRONDHEIM NOR.		BRENDENG	113
1140501	CENTRE RECHERCHES THERMOCHEMIE	MARSEILLE FR.		CAMIA	111
1140602	CENTRE TECHNIQUE ROCLAIN	ROUEN FR.		MUCKENSTURM	123
1180701	POLYTECHNIC SOUTH BANK	LONDON S.E.1 UK		SCOTT	333
1180802	HEXAGON HOUSE	MANCHESTER UK		WALKER	113
1320901	SCIENTIFIC INDUSTRIAL RES.	LOWER HUTT NZ		MAUTNER	123
1021003	DEPARTMENT OF PUBLIC WORKS	OTTAWA CAN		LAYCRAFT	113
1021101	DOMTAR LIMITED	SENNEVILLE CAN.		SHERRY	313
1181202	ELECTRICITY COUNCIL RESEARCH	CAPENHURST UK.		DICKSON	123
1311302	KELVINATOR AUSTRALIA LTD	ADFLAIDE AUS.		CHRISTOPHERSEN	113
1121402	TEKNOLOGISK INSTITUT	KOBENHAVN DENMARK		SVENNINGSEN	113
1191507	UNIVERSITEIT TE LEUVEN	HEVERLEE NE		MYNCKE	123
1141600	CENTR SCIENT TECHN BATIMENT	PARIS-XVI FR		CROISET	333
1411700	UNIVERSITAT KARLSRUHE	KARLSRUHE GFR		BIER	333
1141803	SAINT-GOBAIN	RANTIGNY 60 FR		FOURNIER/KLARSEFELD	113
1211902	YAMAGATA UNIVERSITY	YAMAGATA JAPAN		SUGAWARA	121
1172001	LUND INSTITUTE OF TECHNOLOGY	LUND 7 SWED		RANKVALL	123
1172101	GULLFIHER AB	BILLESOLM, SWED		LINDROTH	113
1152202	POLITECNICO TORINO SERVIZIO	TORINO IT		FERRO	113
1022300	BUILDING PRODUCTS OF CANADA	MONTREAL CAN		SMITH/HARRISON	333
1022410	NATIONAL RESEARCH COUNCIL CAN.	OTTAWA CAN.		SHIRTLIFFE	113
1182501	BRITISH CERAMIC RESEARCH	STOKE TRENT UK		PADGETT	121
1022601	CANADIAN INDUSTRIES LTD.	TORONTO CAN.		OSBORNE	313
1192701	I B B C - T N O	DELFT NEDERLAND		VOS	333
1182801	RAPRA	SHREWSBURY UK		HANDS	123

ASTM THERMAL CONDUCTIVITY EQUIPMENT AND STANDARDS SURVEY

SEPT 1973

PAGE -3 -2

***** FOREIGN COUNTRIES *****

CODE ENTR EQUIPM. *--- SIZE --- *--- TEMP --- * --MEASUREMENTS- --- C
 LONG WIDE TKN HOT- COLD DIF
 KFYs

 ***** GUARDED HOT PLATES SQUARE

2150101	0101	1123121	0500	0500	100	900	- 70			1	1	4	1		
2150202	0101	1123122	0300	0300	040	25	-170	30	1	31	22	6	1	20	10
2130304	0101	1123121	1000	1000	120	60	- 35	95		13	33	5	1	20	10
2130304	0201	1123121	400	400	100	750	- 15	735		13	33	5	1	20	10
2160403	0101	1123261	400	400	100	80	- 70	30	1	13	23	5	2	10	02
2160403	0201	1123261	800	800	150	80	- 70	30	1	13	23	5	2	10	02
2140602	0101	1122122	500	500	50	450	20	430	1	11	22	1	1	10	30
2180701	0101	1122122	300	300	50	100	20			11	22			30	
2180802	0101	1122121	300	300	50	15	- 15	30	1	11	22	4	1	30	15
2320901	0101	1123122	300	300	50	150	- 10			11	22	3	2	15	5
2021003	0202	1122121	300	300	50	300	40			11	11	7	11	20	10
2021101	0101	1121122	200	200	34	94	0			1	22	4			50
2311302	0101	1121121	330	330	38	50	0	50		11	11	3	1	30	20
2121402	0201	1123121	400	400	60	60	- 10	60		11	11	4	2	25	5
2191507	0101	1122121	330	330	40	50	- 25	40	1	11	22	3	1	30	20
2191507	0201	1122121	600	600	80	30	10	20		11	22	3	1	30	20
2191507	0301	1122121	330	330	40	0	-160	30	1	11	22	3	1	50	30
2141803	0201	1113121	400	400	40	90	- 20	40	1	11	12	2	1	20	10
2152202	0101	11 1121			100	1000	25	300		11	1	3	111	10	25
2022410	0101	1123122	25	25		250	-100	3	2	13	22	5	2	20	01 1
2022410	0201	1123122	50	50		250	-100	3	2	13	22	5	2	20	01
2022410	0301	1123122	75	75		250	-100	3	2	13	22	5	2	20	01
2022410	0401	1123122	100	100		250	-100	3	2	13	22	5	2	20	01

***** GUARDED HOT PLATES CIRCULAR

2021003	0101	1222121	230		38	1400	40	999	1	11	11	7	11	20	10
2181202	0101	1242141	200		30	1000	20	999	1	14	24	5	2	50	20
2181202	0201	1242141	200		30	800	20	999	1	14	24	5	2	50	20
2121402	0101	1223121	500		80	60	- 10	60		11	11	4	2	25	5 1
2141803	0301	1222141	212		25	700	- 70	40	1	11	2	2	1	50	
2211902	0101	1 2251				650	- 20			1	3	5		15	1
2172001	0101	121314	340		70	85	- 30						1	10	
2152202	0201	12 1142			50	425	-190	400		11	1	3	111	10	25

***** HEAT METERS

2150202	0201	2112221	0500	0500	100	70	- 15	30	1	11		1	2	10	50 1
2130304	0302	2121121	400	400	60	50	- 15	65		13		3	2	40	10
2140602	0202	2112122	300	300	25	200	20	180	1	13		1	2		
2180802	0201	2122121	300	300	50								2		
2191507	1401	2122121	330	330	40	50	- 20	30	1	11		3	2	50	30
2191507	0501	2122121	600	600	100	500	10	450	1	11		3	2	100	50
2141803	0101	2121121	400	400	45	13	33	20		3		4	2	10	1
2211902	0201	2 2251								1	3	5		15	
2172101	0101	2221121	400	400	80	20	0	20		30		4	2	10	3
2022410	0599	2112232			63	230	-100	3	2	13		5	2	30	01 1
2022410	0601	2112232			63	230	-100	3	2	13		5	2	50	01 1
2022601	0101	2141122	203	203	100	50	0	24		11		4	2	15	05
2192701	0101	2212221	250		60	40	- 10			1	1			50	

SEPT 1973

PAGE -3 -3

***** FOREIGN COUNTRIES *****

CODE FNTR EQUIPM. *--- SIZE ---* *--- TMRP ---* *--- MEASUREMENTS ---* C
 LONG WIDE TKN HOT- COLD DIF

KFYS

→ → → →

**** OTHER EQUIPMENT

[illegible]

***** COMMENT CARDS *****

***** EQUIPMENT COMMENTS *****

```

3022401 01 GUARDED HOT PLATES NUMBER UNSPECIFIED ( 7 COM CARDS )
3022401 05 HEAT FLOW METERS NUMBER UNSPECIFIED THICKN UP TO 100 ( 7 COM CARDS )
3022401 06 NRC CYCLIC HEAT METER ( 7 COM CARDS )
3022401 07 NRC PLANE SOURCE ( 7 COM CARDS )
3022401 08 PITTSBURG CORNING PROBES NUMBER UNSPECIFIED ( 7 COM CARDS )
3022401 09 NRC 3/8 INCH PROBES NUMBER UNSPECIFIED ( 7 COM CARDS )
3022401 10 PEAK TIME IMPULSE ( 7 COM CARDS )
3182501 01 R/S 1902 CALORIMETRIC METHOD ( 2 COM CARDS )
3150202 02 500MM GUARDED HOT PLATE TO BE BUILT 1972
3130304 04 KRISCHER AND 3 RADIAL APP DIN ENTWURF 52613
3140401 01 CALVET CALORIMETER (2 COMMENT CARDS)
3171402 01 DIN 52612
3191507 06 WILKES CALORIMETER
3191507 07 SPHERICAL METHOD
3182801 01 UNGUARDED HEATED DISK HOUSE DESIGN

```

***** REFERENCE MATERIALS *****

```

3140401 01 REF MAT QUARTZ (2 COMMENT CARDS)
3141803 01 REF MAT FOAMED SILICA -150 TO 800C
3211902 01 REF MAT FUSED QUARTZ
3182501 01 HIGH TEMP REFRACTORY INSULATION (2 COM CARDS)

```

***** FOREIGN COUNTRIES *****

***** END *****

ASTM THERMAL CONDUCTIVITY EQUIPMENT AND STANDARDS SURVEY

SEPT 1973

PAGE -4 -1

***** CODING SYSTEM *****

1 CARD IDENTIFICATION 1-NAME 2-EQUIPMENT, 3-COMMENT
 2 TO 3 COUNTRY CODE AS FOLLOWS

AMERICA		EUROPE		ASIA	
U.S.	01	BELGIUM	1-1	JAPAN	2-1
CANADA	02	DENMARK	1-2		
		FINLAND	1-3		
		FRANCE	1-4		
		ITALY	1-5		
		NORWAY	1-6		
		SWEDEN	1-7		
		UNITED KINGDOM	1-8		
		NETHERLANDS	1-9		
		GERMANY	4-1		
				OTHER	
				AUSTRALIA	3-1
				NEW ZEALAND	3-2

4 TO 5 CONSECUTIVE LISTING NUMBER
 6 TO 7 NUMBER OF ENTRIES IN EQUIPMENT LISTING (CARD 2)

***** CARD NUMBER 1 ONLY

9 TO 38 ORGANIZATION NAME
 40 TO 58 LOCATION (TOWN AND COUNTRY)
 59 TO 76 INDIVIDUAL ANSWERING QUESTIONNAIRE

ANSWERS TO QUESTION 10, 11 AND 12

1 - YES , 2 - MAYBE , AND 3 - NO

78 Q-10 WILLING TO PARTICIPATE IN MEASUREMENTS
 79 Q-11 WILLING TO BUY SAMPLES
 80 Q-12 SUGGESTS OTHER MATERIALS FOR STANDARDS

ASTM THERMAL CONDUCTIVITY EQUIPMENT AND STANDARDS SURVEY

SEPT 1973
PAGE -4 -2

***** CARD NUMBER 2 ONLY

9 - 10 SEQUENCE NUMBER OF THIS ENTRY

11 - 12 NUMBER OF PIECES OF EQUIPMENT OF THIS TYPE

***** APPARATUS DESCRIPTION *****

- 14 APPARATUS TYPE
1 GUARDED HOT PLATE
2 HEAT FLOW METER
3 GUARDED HOT BOX
4 UNGUARDED HOT BOX
5 PIPE
6 PROBE
9 OTHER
- 15 SAMPLE CONFIGURATION
1 SQUARE
2 ROUND
3 RECTANGULAR
4 CYLINDRICAL
5 POWDER
6 SPHERE
- 16 NUMBER OF SAMPLES REQUIRED
1 ONE
2 TWO
3 EITHER
4 NOT DEFINED
- 17 ORIENTATION QUESTION 4
1 VERTICAL
2 HORIZONTAL
3 VARIABLE
- 18 DIRECTION OF HEATFLOW QUESTION 5
1 FIXED
2 VARIABLE
- 19 ENVIRONMENT OF OPERATION QUESTION 3
1 VACUUM ONLY
2 ATMOSPHERIC ONLY
3 PRESSURE ABOVE 1 ATM ONLY
4 VACUUM TO ATMOSPHERIC
5 ATMOSPHERIC TO PRESSURE
6 ALL
- 20 CONTROL OF CONTACT PRESSURE QUESTION 7
1 NO
2 YES

ASTM THERMAL CONDUCTIVITY EQUIPMENT AND STANDARDS SURVEY

SEPT 1973
PAGE -4 -3

***** SAMPLE SIZE (IN MILLIMETERS) *****

22 - 25 LENGTH OR DIAMETER
 27 - 30 WIDTH
 32 - 34 THICKNESS

***** OPERATING TEMPERATURES (C) *****

36 - 39 MAX. HOT FACE
 41 - 44 MIN. COLD FACE
 46 - 48 TEMPERATURE DIFFERENCE (999 INDICATES 1000 C OR HIGHER)
 50 1 INDICATES THAT TEMP. DIF. GIVEN IS MAXIMUM
 2 INDICATES THAT TEMP. DIF. GIVEN IS MINIMUM

***** MEASUREMENTS QUESTION 8 *****

52 **TEMPERATURE
 TEMPERATURE PROBE TYPE
 1 THERMOCOUPLES
 2 THERMISTOR
 4 OTHER
 3 PLATINUM
 53 TEMPERATURE DETECTION
 1 POTENTIOMETER
 2 RECORDER
 3 MULTIPLE
 4 OTHER

55 ** POWER
 POWER TYPE
 1 A.C.
 2 D.C.
 3 BOTH
 56 POWER DETECTION
 1 WATTMETER
 2 POTENTIOMETER
 3 OTHER OR MULTIPLE

58 THICKNESS DETECTION
 1 SAMPLE
 2 SPACERS
 3 CALIPERS
 4 MICROMETER
 5 COMBINATION
 6 FIXED STOPS
 7 NOT SPECIFIED

60 ** CALIBRATION
 APPARATUS CALIBRATION
 1 ABSOLUTE
 2 REFERENCE SAMPLE
 61 THERMOCOUPLES 1 INDICATES CALIBRATED
 62 INSTRUMENTS 1 INDICATES CALIBRATED
 64 - 66 ACCURACY - QUESTION 9A XX.X
 68 - 70 PRECISION - QUESTION 9B XX.X
 72 COMMENTS (REFERENCE TO COMMENT CARD 3)

***** END *****

ASTM THERMAL CONDUCTIVITY EQUIPMENT AND STANDARDS SURVEY

SEPT 1973

PAGE -4 -4

CODING SYSTEM EXAMPLE

CARD 1 NAME

KEYS

CODE	ORGANIZATION	TOWN	STATE	NAME	STD
1011108	MCDONNELL DOUGLAS CORP	SAINT LOUIS	MO	MCCRARY	113

SECTION 1 IDENTIFICATION

- x CARD IDENTIFICATION (-1- NAME)
 xx COUNTRY OF ORIGIN CODE (-01- UNITED STATES)
 xx CONSECUTIVE LISTING NUMBER (-11)
 xx NUMBER OF ENTRIES IN EQUIPMENT LISTING ON CARD 2 (-08- ENTRIES)

SECTION 5 REFERENCE MATERIAL QUESTIONS

- x REFERENCE MATERIAL QUESTIONS IF 1 -YES ,2 -MAYBE ,3 -NO
 x WILLING TO PARTICIPATE IN MEASUREMENTS (1 -YES)
 x WILLING TO BUY SAMPLES (1 -YES)
 x SUGGESTS OTHER MATERIALS FOR STANDARDS SEE COMMENT CARD 3 (3 -NO)

ASTM THERMAL CONDUCTIVITY EQUIPMENT AND STANDARDS SURVEY

SEPT 1973

PAGE -4 -5

CARD 2 EQUIPMENT

KFYS

```

-----
CODE  ENTR EQUIPM. *--- SIZE ---* *--- TEMP -----* *MEASUREMENTS-----* C
--1--- --2- --3--- --4--- --5----- --6----- --7--- 8
2011108 0301 1221141 356          50 250 -195          11 22 1 50

```

SECTION 1 IDENTIFICATION

```

X      CARD NUMBER(-2)
XXXX   IDENTIFICATION (-0111 )
XX     ENTRIES(-08)

```

SECTION 2 ENTRIES

```

XX     -03- (NO. 3 OF 8 ENTRIES)
XX     -01- (1 PIECE OF EQUIPMENT OF THIS TYPE)

```

SECTION 3 EQUIPMENT

```

X      -1- (GUARDED HOT PLATE)
X      -2- (ROUND)
X      -2- NUMBER OF SAMPLES REQUIRED (2)
X      -1- ORIENTATION (VERTICAL)
X      -1- DIRECTION OF HEAT FLOW (FIXED)
X      -4- ENVIRONMENT OF OPERATION ( VACUUM TO ATM.)
X      -1- CONTROL OF CONTACT PRESSURE (NO)

```

SECTION 4 SIZE OF SAMPLE

```

XXX    DIAMETER (356 MM)
XXX
XX     THICKNESS (50 MM)

```

SECTION 5 TEMPERATURES DEG. C

```

XXXX   MAX. HOT FACE (250 C)
XXXX   MIN. COLD FACE (-195 C)
XXX    TEMPERATURE DIFFERENCE NOT SPECIFIED
X      TEMP. DIF. IS MAX OR MIN (NOT SPECIFIED)

```

SECTION 6 MEASUREMENTS

```

*** TEMPERATURES
X      PROBE TYPE (-1 THERMOCOUPLES)
X      DETECTION (-1 POTENTIOMETER)
*** POWER
X      TYPE (-2 D.C.)
X      DETECTION (-2 POTENTIOMETER)
*** THICKNESS
X      THICKNESS DETECTION (NOT SPECIFIED)
*** APPARATUS CALIBRATION
X      (-1 ABSOLUTE)
X      THERMOCOUPLE (NOT SPECIFIED)
X      INSTRUMENTS (NOT SPECIFIED)

```

SECTION 7 AND 8

```

XXX    ACCURACY (50 ±5 PCT)
XXX    PRECISION (NOT SPECIFIED)
X      COMMENT CARD REFERENCE (NONE)

```

ASTM THERMAL CONDUCTIVITY EQUIPMENT AND STANDARDS SURVEY

SEPT 1973

CARD 3 COMMENTS

PAGE -4 -6

KEYS

CODE EN COMMENTS
 ---1--- -2 -----COMMENTS
 3011108 07 TANK CALORIMETER

SECTION 1 IDENTIFICATION
 X CARD NUMBER (-3)
 XXXX IDENTIFICATION (-0111)
 XX ENTRIES (-08)

SECTION 2 ENTRIES
 XX ENTRY REFERENCE TO CARD 2 (ENTRY 07)

SECTION 3 COMMENTS

***** END *****

COLUMN NUMBER FOR IBM CARDS

11111111112222222222333333333344444444445555555555666666666677777777778
 1234567890123456789012345678901234567890123456789012345678901234567890

APPENDIX E

OTHER METHODS TO MEASURE HEAT TRANSPORT

**THIS PAGE
WAS INTENTIONALLY
LEFT BLANK**

APPENDIX E

Other Methods to Measure Heat Transport

While the ASTM methods described in Appendix C may be considered the accepted standards by the industry, many other types and forms of k -measuring apparatuses have been used by many investigators on insulating materials. The following is not intended to be a complete listing or description of these other methods, but rather to illustrate the diversity of approaches available to the investigator of thermal conduction phenomena.

E-1 RADIAL HEAT FLOW METHODS

The ASTM C 335 pipe insulation tester is a radial heat flow device, but by design is a system tester as opposed to a material tester. Most radial apparatuses are significantly more sophisticated and refined than the ASTM device and are often research tools. For a thorough discussion of radial heat flow apparatuses, the reader is referred to McElroy and Moore.¹ Herein we will briefly describe only a few apparatuses that have been used on insulating materials.

Flynn² developed the guarded radial heat flow apparatus shown in Fig. E-1 for measurements on powders and loose-fill insulations over a wide temperature range with an estimated absolute accuracy of $\pm 3\%$. The sample fills the annular space between the axial heater and the outer ceramic shell. The ΔT through the sample is measured from the core heater axis to the center of the outer wall and is adjusted for the small temperature drops across the ceramic pieces. Longitudinal temperature uniformity is achieved by use of the independently controlled heaters on the ends of both the core heater and the outer ceramic tube. Temperatures are sensed with Pt-10% Rh vs Pt thermocouples; this sets the upper temperature limit at about 1500°C (2730°F). A feature of this apparatus is that the measuring thermocouples are in a clean environment external to the specimen itself and therefore should maintain their calibration accuracy. A second benefit of this arrangement is that the

Fig. E-1. Radial Flow Method for Powders and Particulate Materials. A, terminal head for current and voltage leads; B, ceramic support tube; C, upper support heater; D, upper shell heater; E, main shell heater; F, ceramic core; G, specimen; H, ceramic shell; I, shell insulation; J, stainless steel case; K, lower support heater; L, lower shell heater; M, ceramic support rod; N, removable plug; T, thermocouple. From A. W. Pratt, Chap. 6 in *Thermal Conductivity*, Vol. 1, Academic Press, London, 1969. Reproduced by permission of Academic Press.

thermocouples on the outer tube are in good thermal contact with a moderately high-conductivity solid. This minimizes the problem of errors arising from heat leaks down thermoelements when they are in poor contact with an insulating material. The situation with the movable axial thermocouple is not so favorable, however, since it is not in good thermal contact with the ceramic core heater. Its depth of immersion in the axially isothermal central hole seems to be sufficient to ensure an accurate measurement.

Godbee and Ziegler³ described a radial apparatus used for measurements on loose powders to 850°C (1560°F). Their apparatus, shown in Fig. E-2, used a metal can container for the powder sample with thermocouples extending through the sample longitudinally. The can was held in a four-zone surrounding furnace, which determined the mean temperature of the experiment. Of special interest in this work was the fact that the apparatus was operated in both the steady-state and transient modes, with results agreeing within about 7%. Also, a very significant

Fig. E-2. The Powders Radial Heat Flow Apparatus of Godbee and Ziegler.³

observation was made concerning hysteresis in their results. Thermal expansion mismatch between the can and the powder sample caused mechanical pressure to be exerted on the powder upon cooling, with the result that the measured k was doubled. This clearly illustrates the effect that the apparatus itself may have on the results of an experiment and shows the kind of detail that must be considered in any apparatus design or application.

The radial heat flow apparatus developed at ORNL has been used for measurements on powders^{4,5} and on rigid insulations.⁶ The basic features of the apparatus, which is described elsewhere,⁷ are shown in Fig. E-3. For rigid materials such as the oriented fibrous carbon-carbon insulation,⁶ the sample consists of stacked disks suitably instrumented at

UNCLASSIFIED
ORNL-DWG 63-7619

Fig. E-3. The ORNL Radial Heat Flow Apparatus as Used for Rigid Samples. From Godfrey et al.⁷

two radii for the ΔT determinations. Care is taken to ensure that the thermocouple immersion depth in the isothermal hole is sufficient. As with Flynn's apparatus,² the muffle heater has three independently controlled sections, and end guard heaters are employed to minimize axial heat flows. A variety of core heater designs has been used with the apparatus, depending upon the particular requirements of the experiment. For measurements on powders, the canister containing powder, shown in Fig. E-4, was substituted for the stack of disks, and the system resembles that of Flynn. A significant difference is the core heater, which in the present case is a directly heated, thin-wall metal tube with the five thermocouples welded directly to the tube wall. Auxiliary heaters are affixed to the ends of the core heater to further

Fig. E-4. Powder Can that Replaces the Sample Disks in the ORNL Radial Heat Flow Apparatus. Lavite bushings insulate the axial core heater from the can. From Godfrey et al.⁵

minimize axial heat leaks. Perhaps the most important aspect of the ORNL radial apparatus is that it has been thoroughly modeled by a finite difference heat conduction computer program⁸ to study configurational variables, extraneous heat flows, and other causes and effects.

Radial techniques have also been used for measurements on super-insulators at cryogenic temperatures. One such apparatus is shown in Fig. E-5, where inward-flowing heat is measured calorimetrically by the boiling cryogenic liquid.⁹ Temperatures may be measured at several points through the insulation thickness or only at the surfaces. By the use of various liquids in the inner chambers, measurements may be made over a wide temperature range. Spherical rather than cylindrical

Fig. E-5. Radial Flow Thermal Conductivity Calorimeter for Super-Insulations. From A. W. Pratt, Chap. 6 in *Thermal Conductivity*, Vol. 1, Academic Press, London, 1969. Reproduced by permission of Academic Press.

geometry has been used often for measurements at cryogenic temperatures. Two such systems are shown in Fig. E-6: an inflow and an outflow device.

Fig. E-6. Spherical Thermal Conductivity Methods. (a) Liquid on both sides, (b) core electrically heated. From P. E. Glaser et al., NASA-SP-5027 (1967).

In Fig. E-6(a) the hot surface temperature may be measured directly, as shown, or it may be assumed to be at the temperature of the bath. For the outflow case, Fig. E-6(b) heat is supplied electrically, the inner temperature is measured directly, and the outer is assumed. While these spherical methods are basically simple, difficulties in specimen preparation, nonuniformity of heat flow, and problems associated with heat leaks present formidable barriers to their use.

An interesting dynamic method of determining k by a radial heat flow method conceived by Gibbon et al.¹⁰ is shown in Fig. E-7, where a large thermal mass is encapsulated by the insulation. The isothermal composite is plunged into an environment at a different temperature, and the time rate of change of the thermal mass is determined. After a sufficient time has elapsed, the insulation is in a pseudo-steady state and its conductivity may be calculated. Gibbon claims 5% agreement with other methods and a significant saving in time.

Fig. E-7. Non-Steady-State Thermal Conductivity Tester. From P. E. Glaser et al., NASA-SP-5027 (1967).

E-2 FLAT PLATE OR DISK METHODS

There is an endless variety of flat plate or disk-type thermal conductivity devices, either absolute or comparative, which have the advantages of speed and small samples. A detailed discussion of each is beyond the scope of the present work. We will, therefore, describe only a few of the most commonly used or interesting methods.

Franci and Kingery¹¹ developed a comparative method shown schematically in Fig. E-8. It has been widely used and misused by many workers. In principle, the thermal conductivity of the specimen is obtained by comparison with the "known" thermal conductivity of the standards, which actually serve as heat meters. The specimen assembly is guarded by the cylindrical heater, whose thermal gradient is matched to that of the stack. Unfortunately this method is fraught with very severe sources of error, which are all too often overlooked or ignored. Thorough discussions of these errors have been presented by Laubitz¹² and by Pratt.¹³ High-quality measurements have been made with this type of apparatus, e.g., by Mirkovich,¹⁴ who claimed an absolute accuracy of 5% for measurements on dense ceramics. However, more typical of what this method is

Fig. E-8. The Comparative or Disk Method. Reproduced from *Thermophysical Properties of Thermal Insulating Materials*. ASD-TDR-62-215 (July 1962).

capable of doing is illustrated by the results for TiC shown in Fig. E-9. Data by Vasilos and Kingery¹⁵ obtained in their original apparatus (identified as "comparative") are totally contrary to those of Mirkovich,¹⁴ obtained in his comparative apparatus. The Mirkovich results have been confirmed by other workers.¹⁶⁻¹⁸ This is a prime example of the effect that indeterminate errors can have on thermal conductivity measurements. The problems with this method become even more severe when it is applied to low k thermal insulations. Indeed, the authors think that this method is useless unless the normal geometry is distorted to the extent that it becomes a guarded hot plate or heat flow meter.

Fig. E-9. Thermal Conductivity of TiC by a Comparative Method Using Alumina Standards. Results of Vasilos,¹⁵ Taylor,¹⁶ and Mirkovich.¹⁴ Reproduced from Mirkovich¹⁴ by permission of the American Ceramic Society.

Flynn and Didion¹⁹ have described a high-temperature disk-type apparatus that resembles the ASTM C 201 Refractory Tester with the important exceptions that it uses a 0.15-m-diam (6-in.) specimen and a steam calorimeter rather than the larger ASTM specimen and water-flow calorimeter. The apparatus, shown schematically in Fig. E-10, employs a SiC diffuser slab like that of C 201, and the specimen is instrumented in the same fashion. It was claimed that the steam calorimeter had significant advantages over the water-flow calorimeter and that the apparatus had an overall accuracy of better than 5%.

Fig. E-10. Steam Calorimeter Apparatus for Measuring Thermal Conductivity of Refractories. From Flynn and Didion.¹⁹

Black et al.²⁰ developed a single-guarded-cold-plate apparatus, shown in Fig. E-11, that is obviously much simpler than their later

Fig. E-11. Single-Guarded-Cold-Plate Thermal Conductivity Apparatus. Reproduced from P. E. Glaser et al., NASA-SP-5027.

double-guarded apparatus (ASTM C 745). This method has been widely applied for measurements at cryogenic temperatures on superinsulations and is estimated to have an accuracy on the order of 10%. As with all flat-plate apparatuses, the possible large differences in contact resistance between the test sample and the plates are difficult to detect or correct.

Hickman²¹ has described a simple version of the guarded hot box method (C 236) that is shown in Fig. E-12. The 0.90-m-square by 0.10-m-thick (35 by 35 by 4 in.) sample forms the lid of a heated box. Copper sheets distribute measured heat uniformly throughout the box, while a guard heater arrangement prevents heat losses. A cold sink at 195 K (-108°F) is provided by an insulated layer of solid CO_2 .

Fig. E-12. Guarded Hot Box Method for Heat Transfer Through Panels at Low Temperatures. Reproduced from Hickman²¹ by permission of Academic Press.

Workers in Italy²² have gone to the other extreme by constructing the double hot box shown in Fig. E-13, which can accommodate wall panels up to 3×3 m (118×118 in.). In this apparatus, there is a symmetrical bidirectional heat flow from the central hot room, through two identical specimens of walls, to two external cold rooms. Essentially, then, this apparatus is a very large version of the two-sample guarded hot plate. It must be noted, however, that the quantity measured here is a thermal transmittance (including film coefficients) and not conductivity.

Fig. E-13. A Double Hot Box Apparatus. 1. Fans — 2. Refrigerating coils — 3. Electrical resistances — 4. Light-reflecting screens — 5. Heat insulation — 6. Air partition — 7. Wall specimens. From Codegne and Ferro.²²

E-3 TRANSIENT METHODS

Because steady-state measurements on thermal insulations are normally very time-consuming — up to two days per data point — transient methods are very attractive. In general, all transient techniques are based upon the determination of the time-temperature response of a point at or near a source of steady heat suddenly applied to an isothermal body. Depending upon the particular experimental arrangement and the boundary conditions, the thermal conductivity (and in some instances, the thermal diffusivity) may be obtained graphically or analytically, often with the aid of a computer.

A typical experimental arrangement for the line source method used by Underwood and McTaggart²³ is shown in Fig. E-14. The sample is 50 to 100 mm (2–4 in.) in size, divided into equal halves. The fine heater wire and nearby thermocouple are tightly clamped between the two pieces. A second thermocouple is used to detect thermal equilibrium. A steady current is then applied to the heater wire, and a continuous record of

Fig. E-14. Schematic Arrangement for Line Source dc Heating Method. B, constant-voltage dc source; H, line source; A, milliammeter; P_1 , potentiometer; P_2 , preamplifier; RE, recorder; R_1 , R_2 , R_3 , resistors; S, switch (SPST); T_1 , T_2 , thermocouples; TC, reference junction. Reproduced from Underwood and McTaggart²³ by permission of Academic Press.

temperature change with time is obtained over a period of several minutes. From the measured power, Q , and the observed temperature change, ΔT , between times t_1 and t_2 , a graphical or least squares solution of

$$k = \frac{Q}{4\pi \Delta T} \ln \left(\frac{t_2 - t_c}{t_1 - t_c} \right) \quad (\text{E-1})$$

yields the conductivity, k , where t_c is an empirical time factor, experimentally determined for each particular sample. This time factor correction accounts for lags and contact resistances. Considering its apparent simplicity, the line source method should be attractive, but because of uncertainties introduced by the effects of contact resistance, temperature fluctuations or drift during the test, and other factors, it has found limited use.

A variation of the line source method, the needle probe, is somewhat more popular and has been used extensively for measurements on many types of low-conductivity materials.²⁴⁻²⁷ A typical probe is shown in Fig. E-15. At best, the design of a probe is a compromise between many competing factors. A single probe is optimum for only one sample — its use with another sample is likely to give meaningless results. Wechsler and Kritz²⁸ have given a very detailed account of the performance of a

Fig. E-15. Schematic Diagram of Thermal Conductivity Probe. Reproduced from Pratt¹³ by permission of Academic Press.

number of needle probes used for studies on foams, powders, and rocks. They theoretically analyzed the performance of representative probes in a given sample and then actually constructed and tested many of the designs to substantiate the predictions. They concluded that well-designed thermal conductivity probes could be suitable for laboratory and field measurements of dry soils and insulating materials. They found that probes optimized for insulations were extremely delicate and recommended that extensive development and testing of the needle probe be undertaken since the method shows considerable promise.

A second class of transient techniques is gaining importance in the area of thermal transport properties; this is the planar source of heat, often termed the plane probe. As the name implies, this method employs a planar source of heat as opposed to a line source. Proponents of the planar approach claim that problems of uncertain interfacial resistance with the line source heater are largely eliminated by their method. The mathematical solutions to the planar problem are similar to those of the line source, and they are subject to similar sets of

boundary conditions. Several different examples of the plane probe will be briefly described in order to illustrate this method.

Halteman and Gerrish²⁹ report a technique based on a semi-infinite slab technique with a constant-temperature surface distant from the heat source. The transient temperature response of the heated face was monitored and used for the solution of the heat conduction equations. They also investigated the effect of a finite-mass heater and found it to be a significant possible source of error.

Jury and Godfrey³⁰ made a detailed analysis of the plane probe and developed an improved method that recognized the contributions of the previous investigators. Semi-infinite slab analysis is applied, and finite difference computer calculations were used to study edge effects and other possible error sources. The experimental arrangement is illustrated in Fig. E-16. The very thin copper-clad Kapton* heater supplies bidirectional heat to the probe backing material (an elastomeric solid) and the sample. Conductivity and diffusivity of the backing material are required in the analysis and are determined in preliminary experiments in which the elastomer is also the sample. The transient temperature response of a single point in the sample 6 mm (1/4 in.) from the heater is monitored by a computer-operated data acquisition system, which also controls the entire experiment and performs the final calculations. An accuracy of about $\pm 5\%$ and a precision of about $\pm 2\%$ have been obtained on gum rubber and Pyroceram.[†]

Grunert et al.³¹ developed another plane probe technique for measurements on multilayer super-insulations. In their method, experimental temperature-time data from a number of points within the sample are used in a finite-difference data reduction program to evaluate k at any specified temperature. They discuss the limitations and advantages of the method in some detail and show that the transient results are within $\pm 30\%$ of values obtained via steady-state measurements. This agreement is considered quite good for measurements on super-insulators.

*Trademark, E. I. du Pont.

[†]Trademark, Corning Glass Works.

Fig. E-16. Schematic Drawing of the ORNL Plane Probe.³⁰

E-4 REFERENCES

1. D. L. McElroy and J. P. Moore, "Chapter 4: Radial Heat Flow Methods for the Measurement of the Thermal Conductivity of Solids," pp. 186-239 in *Thermal Conductivity*, Vol. 1, ed. by R. P. Tye, Academic Press, London, 1969.
2. D. R. Flynn, *J. Res. Nat. Bur. Stand.* 676: 129 (1963).
3. H. W. Godbee and W. T. Ziegler, "The Thermal Conductivity of MgO, Al₂O₃, and ZrO₂ Powders to 850°C," pp. 557-612 in *The 3rd Conference on Thermal Conductivity*, Vol. II, Sessions IV, V, VI, Oak Ridge National Laboratory, Oak Ridge, TN, 1963.

4. J. P. Moore, D. L. McElroy, and R. S. Graves, "Thermal Conductivity of a 58% Dense MgO Powder in Nitrogen," p. 711 in *Thermal Conductivity, Nat. Bur. Stand. Spec. Publ. 302*, ed. by D. R. Flynn and B. A. Peavy, Jr., National Bureau of Standards, Washington, D.C., September 1968.
5. T. G. Godfrey, D. L. McElroy, and J. P. Moore, "Development of a Powders Radial Heat Flow Apparatus: Measurements on Sodium Chloride and Magnesium Oxide," pp. 102-103 in *Program and Abstracts, 12th Int. Conf. Thermal Conductivity, University of Alabama in Birmingham, 1972*.
6. T. G. Godfrey, D. L. McElroy, and Z. L. Ardary, *Nucl. Technol.* 22: 94-107 (1974).
7. T. G. Godfrey, W. Fulkerson, T. G. Kollie, J. P. Moore, and D. L. McElroy, *Thermal Conductivity of Uranium Dioxide and Armco Iron by an Improved Radial Heat Flow Technique*, ORNL-3556 (June 1964).
8. W. D. Turner and M. Simon-Tov, *HEATING-3 - An IBM 360 Heat Conduction Program*, ORNL/TM-3208 (1971).
9. R. H. Kropschot et al., "Multiple-Layer Insulation," pp. 189-198 in *Advances in Cryogenic Engineering*, Vol. 5, ed. by K. D. Timmerhaus, Plenum Press, New York, 1960.
10. N. C. Gibbon, L. C. Matsch, and D. I.-J. Wang, "A Nonsteady-State Thermal-Conductivity Tester for Cryogenic Insulations," pp. 61-73 in *Thermal Conductivity Measurements of Insulating Materials at Cryogenic Temperatures, Spec. Tech. Publ. 411*, American Society for Testing and Materials, Philadelphia, 1967.
11. J. Francis and W. D. Kingery, *J. Am. Ceram. Soc.* 37(2, Pt. II): 80-84 (1954).
12. M. J. Laubitz, "Chapter 3: Measurement of the Thermal Conductivity of Solids at High Temperatures by Using Steady-State Linear and Quasi-Linear Heat Flow," pp. 111-183 in *Thermal Conductivity*, Vol. 1, ed. by R. P. Tye, Academic Press, London, 1969.
13. A. W. Pratt, "Chapter 6: Heat Transmission in Low Conductivity Materials," pp. 301-405 in *Thermal Conductivity*, Vol. 1, ed. by R. P. Tye, Academic Press, London, 1969.

14. V. V. Mirkovich, *J. Am. Ceram. Soc.* 48(8): 387-91 (1965).
15. T. Vasilos and W. D. Kingery, *J. Am. Ceram. Soc.* 37(2, Pt. II): 409-414 (1954).
16. R. E. Taylor, *J. Am. Ceram. Soc.* 44(10): 525 (1961).
17. R. W. Powell and R. P. Tye, "The Thermal Conductivity of Some Electrically Conducting Compounds," pp. 243-257 in *Special Ceramics 1964*, ed. by P. Popper, Academic Press, London and New York, for the British Ceramic Research Association, 1965.
18. M. Hoch and J. Vardi, *J. Am. Ceramic Soc.* 46: 245 (1963).
19. D. R. Flynn and D. A. Didion, "A Steam Calorimeter Apparatus for Refractories," pp. 81-90 in *Conference on Thermal Conductivity*, Battelle Memorial Institute, Columbus, Ohio, 1961.
20. I. A. Black, A. A. Fowle, and P. E. Glaser, *Proc. Xth Int. Conf. Refrig. Inds.*, Copenhagen, 1959.
21. M. J. Hickman, *Proc. IXth Int. Conf. Refrig. Inds., Commission II*, Paris, 1955.
22. C. Codegdne and V. Ferro, "Experimental Apparatus for Thermal Transmittance Measurement Through Large Size Walls," pp. 1115-1123 in *Thermal Conductivity*, ed. by C. Y. Ho and R. E. Taylor, Plenum Press, New York, 1969.
23. W. M. Underwood and R. B. McTaggart, *Storrs Chem. Eng. Progr. Symp. Ser.* 56(30): 261 (1960).
24. F. C. Hooper and F. R. Lepper, *Trans. Am. Soc. Heat. Vent. Eng.* 56: 309 (1950).
25. D. D'Eustachio and R. E. Schreiner, *Trans. Am. Soc. Heat. Vent. Eng.* 58: 331 (1952).
26. W. Woodside and J. H. Messmer, *J. Appl. Phys.* 32: 1688 (1961).
27. A. E. Wechsler and P. E. Glaser, *Icarus* 4: 335 (1965).
28. A. E. Wechsler and M. A. Kritz, "Development and Use of Thermal Conductivity Probes for Soils and Insulations," p. II-D in *The Fifth Conference on Thermal Conductivity*, Vol. 1, Denver University, Denver, Colorado, 1965.

29. E. K. Halteman and R. W. Gerrish, Jr., "Thermal Diffusivity Measurements from a Step Function Change in Flux Into a Double Layer Infinite Slab," pp. 507-512 in *Thermal Conductivity, Nat. Bur. Stand. Spec. Publ. 302*, National Bureau of Standards, Washington, D.C., 1968.
30. S. H. Jury and T. G. Godfrey, *A Transient Method for Rapidly Measuring Thermal Conductivity and Diffusivity of Salt Mine Core Samples (The Plane Probe)*, ORNL/TM-4956 (in preparation).
31. W. E. Grunert, F. Natro, and D. H. Suckow, "A Transient Method for Measuring Thermal Conductivity of Multi-Layer Insulations," pp. 1101-1114 in *Thermal Conductivity*, ed. by C. Y. Ho and R. E. Taylor, Plenum Press, New York, 1969.

**THIS PAGE
WAS INTENTIONALLY
LEFT BLANK**

APPENDIX F

EFFECTS AND MECHANISMS IN HEAT TRANSMISSION

**THIS PAGE
WAS INTENTIONALLY
LEFT BLANK**

F-1 CONDUCTION IN SOLIDS

A part of the variability of the thermal conductivity of insulations derives from the great variability in the thermal conductivities of solids, both in magnitude and temperature dependence. Klemens¹ notes this is due to the different controlling factors affecting the two principal carriers of heat: lattice waves, which are always present, and free electrons, which are present in metals and semiconductors. The kinetic theory of gases led to an expression for the thermal conductivity of a gas

$$k = (1/3)Cv\bar{l} , \quad (F-1)$$

where v is the average particle velocity, C is the particle specific heat, and $\bar{l}$ is the particle mean free path. In solids each carrier of heat is treated as a particle, and this expression is used to describe the k due to each carrier of heat. The mean free path of these carriers is limited by various scattering mechanisms, and the crucial issue is to define and estimate the mean free path. For instance the conduction electrons interact with the lattice waves, so that the electron mean free path is reduced; but in addition, the mean free path of the lattice waves is also reduced by the very same interaction — hence the temperature variability of k of solids can be explained by this relatively simple model.

It is well known (see Fig. F-1)² that k of crystalline electrical insulators decreases approximately as T^{-1} when the temperature, T , is greater than the Debye temperature, θ_D , of the solid because three-phonon umklapp scattering processes dominate the lattice wave interactions. Analysis of this process has yielded expressions for calculating the thermal resistance ($R = 1/k$)

$$R = 5.88 \times 10^{-25} \gamma^2 T/M\delta(\theta_D)^3 , \quad (F-2)$$

where γ is the Gruneisen constant, M the average mass per atom, and δ the cube root of the atomic volume. This expression gives the proper

Fig. F-1. Thermal Conductivity of Crystalline and Amorphous Electrical Insulators as a Function of Temperature. From Powell et al.²

temperature dependence of R , compares favorably with measurements on certain solids, but often fails due to uncertainties in γ and θ_D .

As shown in Fig. F-1, the k of crystalline solids is considerably larger than that of the amorphous solids, such as fused quartz or glass. This is due to the strong scattering of lattice waves by the defect structure associated with the amorphous structure. This is the basis for using amorphous fibers in insulations. However, it should be noted that at higher temperatures the conduction in the glasses may exceed that of crystalline materials because of radiative processes (transparency).

In metals, where one is dealing with a highly degenerate electron gas and the magnitude of k depends on the electron-phonon interaction, which is difficult to estimate, one often resorts to measurement of auxiliary properties to estimate k . Thus in metals at high temperature the total k is written as the sum of an electronic contribution, k_e , and a lattice contribution, k_l , which are additive since the two processes are acting in parallel:

$$k = k_e + k_l , \quad (F-3)$$

$$= \frac{L(T)T}{\rho} + \frac{A}{T} + \frac{B}{T^2} , \quad (F-4)$$

where the electron contribution is related to the electrical resistivity, ρ , through a Lorenz function $L(T)$, and the lattice contribution is described with the constants A and B . Various studies of $L(T)$, A , and B of the elements allow quite reasonable estimates of k to be obtained from measurements of ρ as a function of temperature.³

Figure F-2 shows the range of k values expected for some pure metals as a function of temperature. It is safe to say that for these pure metals the electronic contribution exceeds 75% of the total thermal conductivity. Since aluminum is used in certain multilayer insulations, this data figure helps to explain the marked anisotropy of conduction in these assemblies; since k parallel to the sheet is that of aluminum, whereas the k perpendicular to the sheets for an air filled system is not far from that of a fiber insulation. Thus, one has an anisotropy ratio of $2.4/(5 \times 10^{-3})$ or about 500, and even greater values obtain for evacuated multilayer insulations.

The foregoing, though incomplete and simplified, is included to provide some insight into the analysis used on well-defined solids to describe the conduction processes occurring therein. Similar analyses are used for insulations, though they may be more complex and different processes are involved.

Fig. F-2. Thermal Conductivity Values of Various Pure Metals as a Function of Temperature. From Powell et al.²

F-2 CONDUCTION IN GASES

In the majority of thermal insulations, the gas phase plays an important role in heat transmission. In the previous section, Eq. (F-1) was presented for the conductivity of a gas in terms of velocity, specific heat, and mean free path. In simple terms, the velocity is proportional to temperature, the specific heat to mass (inversely), and the mean free path to pressure. Figure F-3 shows that the k of various common gases versus temperature at a pressure of 1 atm (0.1 MPa) ranges over almost two orders of magnitude, with the rare inert gases showing the lowest values. Of special interest are the relative positions of Freon, CO_2 , steam, and the components of air in this figure. It is important to note also that k increases rather uniformly with temperature. A detailed discussion of gas conduction is beyond the scope of this report, and the interested reader is referred to the many excellent works on the subject. However, certain specific aspects of gas conduction will be discussed in subsequent portions of this report.

Fig. F-3. Thermal Conductivity of Various Gases at 1 atm (0.1 MPa) as a Function of Temperature.

F-3 CONVECTION AND RADIATION TRANSPORT

Heat transmission in insulations by convection is generally considered to be a low-order effect. However, as will be discussed in following sections, it is not necessarily negligible. Convective heat transfer is another complex subject beyond the present scope, being dependent upon the specific gas properties, geometry of the system, and temperature differences.

Similarly, radiative heat transfer is a complex subject and the topic of numerous texts. Simply stated, radiative heat transmission (in solids as well as in gases) depends upon the emissivities of the

radiating and absorbing elements of the structure, geometric factors, and differences in the fourth powers of the absolute temperatures (normally expressed as $T_{av}^3 \Delta T$). Because of this T^3 dependence, radiative heat transmission is especially important in cryogenic and in high-temperature applications, although subsequent discussions will demonstrate its importance in all thermal insulations.

F-4 HEAT TRANSMISSION AND EFFECTS IN INSULATIONS

This section describes some of the effects of variables that have been observed to change the k of fibrous, granular, cellular, bulk, and multilayered insulations. The primary variables that have been identified in Chap. 3 of this report include temperature, density, moisture, gas, and pressure. Often, studies of these variables included other variations such as fiber dimensions, insulation thickness, fiber opacity, matt anisotropy, and aging effects. It is not physically possible to detail all the variables that can alter an insulation's properties; instead, highlights of selected studies are mentioned.

The range of k values observed and their temperature dependences have been discussed briefly in Chap. 3 and noted in various figures (see, for example, Figs. 5.1, 5.2, and 5.3). The magnitude of heat flow through the insulation depends on the contribution and interaction of the four basic mechanisms, which have been identified as:

1. k_S , solid conduction through the material forming the insulation;
2. k_R , radiation transfer through the voids and components of the insulation;
3. k_C , gas conduction within the voids;
4. k_{CV} , convective transfer in and through the voids.

Pratt⁴ notes (1) that for most thermal insulations all four modes of heat transfer are possible; (2) that the observed thermal conductance may depend on the apparatus, the absolute and differential temperatures used, and the environmental conditions; and (3) in most cases, k_{CV} can be neglected if the void diameters within the sample are less than 2 to 3 mm.

Within the study of heat transmission in insulations formulas have been derived to express k in terms of porosity and the thermal conductivities

of the constituent phases, solid and gas. These formulas consider various physical arrangements: discontinuous solid, continuous gas (fibrous and loose fills); *vice versa* (foams); and continuous networks of both phases.

F-5 FIBROUS INSULATIONS

Fibrous insulations make up a large fraction of all thermal insulations and have been studied quite extensively. For this reason, we present a fairly detailed account of heat transmission effects in fibrous insulations and use this as a base for discussion of the other types, noting those characteristics that are significantly different.

Baxter⁵ and Schuhmeister⁶ derived an expression for various fibers in air, in which the measured value, k_m , was

$$k_m = X(k_1 v_1 + k_2 v_2) + Y \left(\frac{k_1 k_2}{k_1 v_2 + k_2 v_1} \right) \quad (\text{F-5})$$

where k_1 , k_2 , and v_1 , v_2 denote the thermal conductivity and volume fraction of the air and fiber, and $X + Y = 1$. Schuhmeister found $X = 0.33$ and $Y = 0.67$, whereas Baxter found $X = 0.21$ and $Y = 0.79$. Schuhmeister obtained his values by visualizing the fibers as plane slabs, 1/3 parallel to the heat flow direction and 2/3 arranged at right angles to the flow. It is noteworthy that the Baxter values determined for densities in the range 300 to 600 kg/m³ (18 to 37 pcf) describe the k_m results of Godfrey, McElroy and Ardary⁷ on rigid fibrous carbon insulations of density 180 kg/m³ (11 pcf) in argon and nitrogen at low temperatures and allowed a radiative heat transfer component to be obtained at high temperatures.

Strong⁸ has obtained a theoretical expression to estimate the heat conduction along the solid paths of a random arrangement of fibers. A value of 42 μW was calculated for a glass fiber matt of density 250 kg/m³ (15.6 pcf) and having fibers of diameter 3.6 μm , whereas experimental values ranged from 19 to 22 μW .

Numerous studies have noted increases in the total heat transmitted as the density of the insulation decreases below about 100 kg/m³ (6.2 pcf). Figure F-4 shows some of the results obtained by Allcut⁹

Fig. F-4. "Apparent" Thermal Conductivity of Various Materials at Different Densities. A, kapok; B, bagasse; C, corkboard; D, slag wool; E, mineral wool. Reproduced from Pratt⁴ by permission of Academic Press.

on powdered, granular, and fibrous compositions. The increase in heat transmitted is associated with convection or a combination of convection and radiation. The effect of increasing density is to subdivide a single air layer into a series of thinner layers. This suppresses convection currents and decreases heat exchange by radiation. The remaining transfer is then mainly by conduction in air. Allcut further demonstrated that at a constant glass wool insulation density, an increase in the gas pressure resulted in an increase in the convective component of the heat loss.

A hallmark study of how real insulation behaves at conventional temperatures was conducted by Verschoor and Greebler.¹⁰ They tested a series of glass fibrous insulations with densities in the range 8 to 134 kg/m³ (0.5 to 8.4 pcf) in various gases at pressures from 0.001 torr to atmospheric (0.13 Pa to 0.1 MPa) and derived expressions for their results based on the kinetic theory of gases. Their analysis showed the importance of the fiber system on limiting the mean free path of the gas molecule and hence the k of an insulation. They derived an expression for the reduction in k_C by reduction of the mean free path in the insulation l_f compared with that of the free gas l_g as

$$k_C = k_g \frac{l_f}{l_f + l_g}, \quad (\text{F-6})$$

where k_g is the thermal conductivity of the free gas and l_f is $1.57r/f$, where r is the fiber radius and f the volume fraction of fiber. At 338 K, (149°F) pressure decreases l_g as $81/p$, where p is in torr (1 torr = 133 Pa), so by substitution in Eq. (F-6) for k_g the value for air one can obtain

$$k_C = \frac{0.314rp/f}{81 + 1.57rp/f} \quad (\text{F-7})$$

in English units. This expression describes the apparent variation of k_C with pressure for a fibrous insulation in which some control over the important variables can be obtained in manufacture. Figure F-5 shows this variation for an insulation of density 74 kg/m^3 ($\sim 4.5 \text{ pcf}$) at 338 K, as measured by Vershoor and Greebler. The limiting k value $2.3 \text{ mW m}^{-1} \text{ K}^{-1}$ ($0.016 \text{ Btu in. hr}^{-1} \text{ ft}^{-2} \text{ }^\circ\text{F}^{-1}$) at low pressure represents the apparent conductivity by radiation and conduction. At intermediate pressures $l_f \approx l_g$ and k_C increases with pressure until eventually l_g is small compared with l_f , and gas conduction becomes independent of pressure. At atmospheric pressure the enclosed gas is essentially a free

Fig. F-5. Thermal Conductivity Versus Air Pressure for 74 kg/m^3 Type A Insulation at 65°C Mean Temperature. —, Experimental; ---, theoretical (theoretical curve neglects contribution by air convection). Reproduced from Pratt⁴ by permission of Academic Press.

gas and $l_g \ll l_f$. The difference in the calculated and measured curves is associated with convection in the fibrous insulation. Table F-1 shows measured values of k for various gases, gas pressure and insulation densities, all at 338 K (149°F). Computed values of k_{CV} and k_R are included in this table. These results show about a 50% reduction in k by changing from air to Freon 12. The analysis by Verschoor and Greebler suggests an increase in insulation efficiency can be achieved by using a small-diameter fiber, since $l_f \gg l_g$ at atmospheric pressure. Use of a fine fiber, 0.01 μm diam, at a bulk density of 160 kg/m^3 (10 pcf) reduced k by 50%. Very similar results have been obtained by Allcut⁹ on the reduction in k_{CV} with increased density of a fibrous glass, and this is shown in Fig. F-6.

Table F-1. Thermal Conductivity of Type A Fiber Insulation with Different Gases at a Mean Temperature of 338 K and for a Temperature Gradient of 26 K/cm

Gas	Insulation Density (kg/m^3)	Pressure (kPa)	Thermal Conductivity ^a $\text{mW m}^{-1} \text{K}^{-1}$		
			k	k_C	k_{CV}
Helium	8.73	101	219	162	22.8
Helium	24.0	101	192	162	20.8
Helium	24.0	10.1	189	159 ^b	20.0
Helium	74.0	101	181	161	11.7
Air	8.73	101	56.9	29.2	9.1
Air	24.0	101	42.5	29.2	5.0
Air	24.0	10.1	42.2	29.1	4.9
Air	74.0	101	35.6	29.2	3.0
Carbon dioxide	8.73	101	47.0	19.6	8.8
Carbon dioxide	24.0	101	32.5	19.6	4.9
Carbon dioxide	24.0	10.1	32.5	19.6	4.9
Carbon dioxide	74.0	101	25.5	19.6	2.7
Freon-12	8.73	101	37.6	12.0	7.1
Freon-12	24.0	101	23.3	12.0	3.5
Freon-12	24.0	10.1	23.3	12.0	3.5
Freon-12	74.0	101	16.7	12.0	2.0

^aThe difference between the values of k listed and the sum of k_C and k_{CV} is the contribution by radiation and solid conduction.

^bFor helium there is a noticeable difference between k and k_C at 10.1 kPa and even some difference at atmospheric pressure (101 kPa) since the mean free path and the thermal conductivity of this gas are large.

Fig. F-6. Loss by Convection Versus Density of Fiber Glass. Reproduced from Pratt⁴ by permission of Academic Press.

In addition Verschoor and Greebler determined the k of three densities of one insulation as a function of pressure, with the results illustrated in Fig. F-7. The rising asymptote with decreasing density indicates that the heat transferred by radiation increases. This result is analyzed by regarding the insulation as a system of parallel planes, each acting as a radiation barrier. If T_1 is the temperature of the hot surface and there are n radiation barriers with effective emissivity ϵ between the surface and the surroundings at T_2 , then the heat flux H_R radiated by the system is

$$H_R = 6.92 \times 10^{-9} \frac{\epsilon}{n+1} T_m^3 (T_1 - T_2) , \quad (F-8)$$

where $T_m = (T_1 + T_2)/2$. If d is the bulk density of the material, l the thickness of the barrier, and d_s the density of the solid component

$$k_R = 6.92 \times 10^{-9} \pi d_s l T_m^3 / 4 \alpha^2 d , \quad (F-9)$$

where α is the fraction of incident radiant energy absorbed by a single fiber and $1/\alpha^2$ is an opacity factor representing an average value obtained by integrating over the spectral distribution of radiant energy. This expression indicates that the radiant heat conducted is inversely

Fig. F-7. Thermal Conductivity Versus Air Pressure for Three Densities of Type A Insulation at 338 K Mean Temperature. —, Experimental; ---, Theoretical. Reproduced from Pratt⁴ by permission of Academic Press.

proportional to the density of the structure, d . This analysis was extended by Strong et al.⁸ to obtain a similar expression

$$k_R = 9.23 \times 10^{-9} l_{pf} T^3 \quad (\text{F-10})$$

where l_{pf} is the mean free path for photon-fiber collisions. Strong's analysis was supported by experimental radiation heat transfer studies on various glass fibers. Their studies showed an almost insignificant effect on l_{pf} for fibers below 4 μm in diameter. They did define the effective emittance of the fibers, which is the fraction of incident radiation absorbed by a fiber and later reradiated as thermal radiation. Because the transfer by radiation increases significantly with temperature the absorptivity of the fiber becomes important, but with a glass this property can be adjusted by changing its composition.

Figure F-8 summarizes these various components of heat transfer in a fibrous material in air as a function of density. The relative values of the various components change with density because air conduction dominates heat transfer in this density range. As the total k decreases, the relative importance of air increases from about 60% to over 80% of the total k . Obviously control of the continuous gas phase represents a useful area to explore to decrease the effective k of an insulation. Table F-1 indicates that for an insulation density of 24 kg/m^3 (1.5 pcf)

Fig. F-8. Contribution by Each of Mechanisms of Heat Transfer in Type A Insulation at Atmospheric Pressure Versus Insulation Density at 338 K Mean Temperature. Reproduced from Pratt⁴ by permission of Academic Press.

k is $4.25 \times 10^{-2} \text{ W m}^{-1} \text{ K}^{-1}$ ($0.293 \text{ Btu in. hr}^{-1} \text{ ft}^{-2} \text{ }^{\circ}\text{F}^{-1}$) in air, but is $2.33 \times 10^{-2} \text{ W m}^{-1} \text{ K}^{-1}$ ($0.162 \text{ Btu in. hr}^{-1} \text{ ft}^{-2} \text{ }^{\circ}\text{F}^{-1}$) in Freon 12. This represents a reduction in k of about 45%. Other means to reduce k include density increases, gas pressure reduction, and a balance of fiber diameter and density to minimize convection and radiation transport. Suggestions such as these indicate the merit of theoretical analyses of the phenomena occurring in insulations.

Using well-characterized glass fiber insulations, Fournier and Klarsfeld¹¹ measured k from 125 to 300 K (-234 to 80°F) and presented an analysis that predicts the conditions under which natural convective currents exist and what the consequences of these are on overall heat transfer. The fineness index,* F , was measured in both directions for families of insulation products of different apparent mass/volume (ρ) or porosity, and typical results are illustrated in Fig. F-9(a). This shows that the air flow permeability K_1 decreases with increasing ρ and that a lower permeability can be obtained by either increasing ρ with

*Fineness index F is defined from particular air-flow permeability measurement on randomly compacted glass fiber plug of given mass (indicated in grams between parentheses) introduced in rigid cylindrical cell of fixed dimensions. It is only a reference figure without any physical meaning.

Fig. F-9. Relation Among Permeability, Density, Thermal Conductivity, and Fineness Index. (a) Air-flow permeability K_L versus mass/volume ρ for four families of glass fiber materials of four different fineness indices. (b) Thermal conductivity λ^* measured for some glass fiber insulating materials versus mass volume. Iso-fineness mean curves. Reproduced from Fournier and Klausfeld¹¹ by permission of American Society for Testing and Materials.

F constant or decreasing F with ρ constant. The parallel permeability $K_{||}$ was greater than K_L for these insulations; $K_L/K_{||}$ was about 0.5. Thermal conductivity values for these materials are shown in Fig. F-9(b) as a function of ρ and fineness index. Note that k is a function of both variables, indicating that the role of natural convection is more complex than a simple function of ρ . Figure F-10 shows the k vs T results on one type insulation and indicates that below about 200 K (-100°F) neither ρ nor F influences k . These results are used with an analysis of the infiltration Rayleigh Number Ra to show that if Ra exceeds 40 because of the temperature difference, insulating material, and its thickness, then a convection term will exist in the installation. It is shown that by changing the thickness, ρ , or fineness index this effect can be suppressed.

Bankvall¹² provides an accurate, clear, and thorough discussion of the heat transfer behavior in permeable insulating materials such as glass fiber. Measurements from a rapidly responding, rotatable guarded hot plate, which can be evacuated, are presented to illustrate the heat transfer mechanisms including natural convective heat transfer.

Fig. F-10. Thermal Conductivity λ^* Versus Mean Temperature for Glass Fiber Materials. Fineness index 3.8 (5g). Five values are considered for mass/volume. Reproduced from Fournier and Klausfeld¹¹ by permission of the American Society for Testing and Materials.

The radiative contribution to k of fibrous insulations for use at high temperatures in the Space Shuttle program are treated by Linford et al.¹³ Two radiative components are identified as (1) radiation transmission, R_T , which is direct transfer from the hot face to the cold face by a series of scattering reflections at individual fibers and (2) radiation conductivity, R_C , which is absorption and reemission by the fibers. The relative magnitude of these two is determined by the properties of the fibers (diameters, composition, density) and their isotropic emission and scattering properties. Analytical equations were derived for a four-flux model of net radiative transfer, and the appropriate optical parameters were measured for two typical insulations. The results showed that the R_T term was dominant at high temperatures but the R_C term may be important at lower temperatures.

Linford et al.¹³ warn that laboratory k data for fibrous insulations should not be used in thermal design computations unless due regard is taken of the radiative contribution to the total thermal conductivity. Their study provides a valuable extension to the earlier work by Pelanne¹⁴ on separation of the heat transfer mechanisms in low-density fibrous insulations. Pelanne used high- and low-emissivity plates to show that the radiation contribution was more than 30% of the total k and that R_T

exceeded R_c by a factor of 5 to 7 for glass fiber insulation at 24°C (75°F) and a density of 16 kg/m³ (1 pcf). Pelanne's study did not include direct determination of the pertinent optical factors to allow calculation of R_T and R_c . Similar analyses of radiant energy transport have been presented by Hager and Steere,¹⁵ Davis and Birkebak,¹⁶ and Klemens and Greenberg.¹⁷ The last authors point out very effectively that in some cases the radiative thermal conductivity at moderate temperatures is expected to be larger than one would expect by extrapolation from very high temperatures using a T^3 law, and equations to describe this are presented.

Ferro and Sacchi¹⁸ described an automatic square guarded hot plate apparatus for use to 1000°C (1830°F) and reported mean k values for a number of fibrous insulations in air with densities between 40 and 118 kg/m³ (2.5 to 7.4 pcf), as well as higher density asbestos-fiber products, up to 600°C (1112°F). These mean k values involved temperature differences ranging from 60 to 580°C (108–1044°F) through the 25-mm-thick (1-in.) sample, so they deduced empirical representations of k as a function of temperature:

$$k = a + bt + ct^2, \quad (\text{F-11})$$

such that

$$k_{\text{mean}} (t_o - t_a) = a(t_o - t_a) + \frac{b}{2} (t_o^2 - t_a^2) + \frac{c}{3} (t_o^3 - t_a^3), \quad (\text{F-12})$$

where t_o and t_a are the hot and cold face temperatures for a particular application. Their deduced k values are shown in Fig. F-11. They did not attempt to separate the component parts of k .

Measurements¹⁹ to high temperatures on reusable external insulations (REI) similar to those studied by Linford et al.¹³ illustrate some of the experimental difficulties in obtaining valid k values from guarded hot plates and radial outflow techniques. Similarly measurements²⁰ by these two techniques to high temperature (1370°C, ~2500°F) on Dynaquartz,* Dynaflex,* and sapphire wool in air, argon, and vacuum had revealed

*Trade names, Johns-Manville.

Fig. F-11. Thermal Conductivity of Various Thermal Insulations as a Function of Temperature. (a) Glass and rock fibers of various densities. (b) Fibrous and other materials of higher density. Copied from Ferro and Sacchi¹⁸ by permission of Plenum Press.

problems with experimental techniques for fibrous insulation, particularly in vacuum. Rolinski and Purcell²⁰ show by analysis of the mechanisms of heat transport in these materials that the dominant mode of heat transfer is radiation. Pettyjohn²¹ reported k measurements from 400 to 800 K (260 to 980°F) on fibrous silica at various reduced pressures, mean temperatures, and bulk densities. These studies, like the one by Vershoor and Greebler,¹⁰ allowed the magnitudes of the various components to be identified as a function of temperature. Pettyjohn found a significant reduction in the radiation contribution as the density increased from 55 to 149 kg/m^3 (3.4–9.3%) [see Fig. F-12 (a), (b), and (c)], and this made the $k \cdot \text{density}$ product lower for the more dense insulation at intermediate pressures, as is illustrated in Fig. F-12(d). This indicates that this material is more efficient and easier to handle with less bulk volume.

In certain instances where radiative heat transfer is quite important, steps may be taken to minimize it. For example, Rainhart et al.²² found

Fig. F-12. Gas Pressure, Temperature, and Bulk Density Relationships for a High Temperature Fibrous Insulation. From Pettyjohn.²¹ (a) Density = 55 kg/m³. (b) Density = 98 kg/m³. (c) Density = 149 kg/m³. (d) Mean temperature = 780 K.

that very small graphite flakes oriented perpendicular to the heat flow direction reduced the apparent total thermal conductivity, at high temperature, of fibrous carbon insulation of the type measured by Godfrey et al.⁷ The graphite flakes caused an increase in k at the lower temperature because of mass conduction, but this was more than offset by the decrease at very high temperatures, as shown in Fig. F-13. Thus, effective ways may be sometimes found to alter the radiative heat transmission.

Fig. F-13. Thermal Conductivity of Rigid Fibrous Carbon Insulation as a Function of Temperature Showing the Effect of Graphite Flake Additions on Radiative and Conductive Heat Transmission. From Rainhart et al.²²

F-6 CELLULAR INSULATION

These materials have continuous solid phases containing cells, which may be large or small and open or closed. The open cell systems

permit movement of air or vapor through the material, whereas the closed cells resist this movement. The solids used in those materials are generally low- k materials and include plastics (polystyrene, polyvinyl chloride, urethanes), glasses, and concretes. The voids are produced to contain a variety of low-conductivity gases at various internal pressures.

Ball et al.²³ review the factors for use of urethane foams as insulations. The thermal conductivity k is subdivided as

$$k = k_C + k_S + k_R + k_{CV} \quad (F-13)$$

where k_C is for the component associated with conduction through the gaseous phase, k_S for that of the solid phase, k_R for the conductivity component associated with radiation transfer across the cells, and k_{CV} is that for the convective transfer through the gaseous phase and is zero for most foams. Since the gaseous phase occupies about 97% of the volume of foams in the 24 to 48 kg/m³ (1.5–3 pcf) density range k_C is the dominant term. The technical advantage of these materials is associated with retention of low-conductivity gases in closed cells.

Commercial urethane foams are made with various gases, such as CFCl₃, CF₂Cl₂, CO₂, and air, and the low thermal conductivity depends on retention of these gases (see Fig. F-3). Fournier²⁴ and Jones²⁵ have shown that the k of polystyrene foams depends on thickness, which implies a significant k_R term, and the nonlinear k temperature dependence can be explained by using a T^3 term to explain the radiation transfer for the temperature range 15 to 65°C (60–150°F). Tye²⁶ has determined k for a number of cellular materials in the range 100 to 300 K (–280 to 80°F) and has shown k to decrease in this range and to have values less than those of some exfoliated vermiculites. Steinle²⁷ has shown that the low k of polyurethane foams can be maintained only if gaseous diffusion can be prevented. In fact he shows that the gas R-11 is soluble in the solid urethane and that the cell content of R-11 will decrease with time. This is followed by an increase of air content, with a subsequent increase in k_C and hence in k . Ball et al.²³ provide a schematic illustration of

this aging effect due to gaseous diffusion (see Fig. F-14) and suggest various lifetimes expected to reach the indicated plateau areas of $T_C \approx 7$ years and $T_D \approx 200$ years. The latter certainly exceeds the technological interest period. Domínguez et al.²⁸ provide data on a number of cellular materials of densities 16 to 108 kg/m³ (1 to 6.8 pcf) to allow the various heat transfer mechanisms to be identified.

Fig. F-14. Thermal Conductivity as a Function of Time for Urethane Foam. T_A is a short induction period. At T_B , air in the foam has reached atmospheric pressure, diluting the Freon gas. At T_C , all condensed Freon has vaporized. At T_D , all Freon has diffused out of the foam. Reproduced from Ball et al.²³ by permission of Pergamon Press.

Inorganic cellular foams have also been the subject of numerous investigations. These materials may operate over a very wide temperature range (cryogenic to $\sim 500^\circ\text{C}$) and have a load bearing capacity. The gas cells in a typical foamed glass are sufficiently large that the entrapped gas might behave as a free-gas conductor and, in high temperature gradients, may show convective behavior. During manufacture foamed glass assumes some opacity, but we are unaware of any detailed studies of its optical transmission characteristics as they relate to heat transmission. Since glasses are ordinarily transparent to short infrared wavelengths, it would be expected that radiant heat transmission is a significant fraction of the total k in foamed glass. Foams have also been made of the more refractory compounds, such as silicon carbide, zirconia, and alumina, but

have been little studied. Because of the much higher temperatures encountered, the radiation heat transmission in these foams might become very significant.

F-7 GRANULAR INSULATIONS

The effects discussed in the previous section on fibrous insulations are applicable to the granular types in large measure, when the geometry and density factors are taken into account. In general, the densities of granular insulations are somewhat higher than those of fibrous ones, and the particles are significantly larger. Thus, the relative magnitudes of the various heat transfer mechanisms are different, with the gas contribution most affected. (Evacuated powders are a special class to be discussed later.)

Excellent reviews of heat transmission in granular materials have been given by Pratt,⁴ Godbee and Ziegler,²⁹ and Gorrington and Churchill³⁰ who all show that a variety of models may be used to explain or calculate the conductivities of these heterogeneous materials. Unfortunately, the simple models only crudely approximate the observations, while the very elegant models, which closely fit the data, contain so many adjustable parameters that they may be difficult to apply. Nonetheless, serious attempts are being made to quantify the heat transmission characteristics of this important class of thermal insulation.

As for fibrous insulations, numerous formulas have been derived relating the thermal conductivity of a granular material to the volume fractions, f , of the component phases. These models assume various distributions of the solid component, k_S , and the fluid component, k_F , with respect to the heat flow direction, either parallel or series. Pratt¹ reviews the equations for various idealized structures as:

Case 1. Parallel arrangement —

$$k = fk_S + (1 - f)k_F \quad (\text{F-14})$$

Case 2. Series arrangement —

$$k = \frac{k_S k_F}{fk_F + (1 - f)k_S} \quad (\text{F-15})$$

Case 3. Random arrangement —

$$k = k_F (1-f) k_S f \quad (\text{F-16})$$

Case 4. Random arrangement of isolated spheres with k_1 in a continuous medium with k_2 —

$$k = k_2 \left[\frac{1 - 2f \left(\frac{1 - k_1/k_2}{2 + k_1 k_2} \right)}{1 + f \left(\frac{1 - k_1/k_2}{2 + k_1 k_2} \right)} \right] \quad (\text{F-17})$$

Predicted values for k as a function of the volume fraction solid are illustrated in Fig. F-15 for $k_1/k_2 = 0.1$ for these equations. More complex equations have been derived for three-phase materials.

Fig. F-15. Thermal Conductivity of Two-Phase Mixtures Calculated under the Following Assumptions: 1, Minimum Conductivity; 2, Maximum Conductivity; 3, Phase 2 Continuous; 4, Phase 1 Continuous; 5, Random Mixture. Reproduced from Pratt⁴ by permission of Academic Press.

F-8 BULK OR MASS INSULATIONS

This class of insulating materials is of especial importance because it encompasses a large fraction of those used for intermediate and high temperatures. Notable examples are the calcium silicate, perlite, and insulating fire brick (IFB) types. As with the cellular products, the solid is a continuous phase, but the gas is also at least semi-continuous. Perhaps the most significant single product in this class is Min-K (from Johns-Manville), wherein a very special silica aerogel is the base material. The pores in this phase are sufficiently small that the gas conduction is mean-free-path limited, the inter-particle porosity is similarly sized to reduce the bulk-gas effect, and the product is strengthened by incorporation of very small diameter fibers.

Tye³¹ conducted an interesting study on samples of Min-K 2000* with densities in the range 280 to 318 kg/m³ (17.5 to 20 pcf) from 300 to 1000 K (80 to 1340°F) in air, vacuum, and krypton. Values of k in air for four samples showed a spread of less than $\pm 4\%$, which prompted Tye to suggest this material as a reference material. He noted a 25 to 30% anisotropy for strips of Min-K 2000 samples rotated 90°. His results and those of the manufacturer differ by -3.5% at 100°C (212°F) and $+7.5\%$ at 650°C (1200°F).

Mass insulations offer a good illustration of the effects of heterogeneous mixtures of solids. Historically, many of these products were strengthened by an asbestos fiber filler. However, the recent OSHA restrictions on the use of asbestos have caused manufacturers to seek other strengthening fibers, usually of glass. They now find that fiber contents necessary to yield the required strength also yield a conductivity that may be higher than for the earlier product.

F-9 EVACUATED INSULATIONS

Since the gaseous conduction component dominates the thermal conductivity of the insulations discussed above, efforts to remove this component have led logically to evacuated insulations. The evacuated

*Trade name, Johns-Manville.

systems include powders, fibers, and multilayer insulations. Glaser et al.³² have treated these systems in detail. The radiation transfer is reduced for powders and fibers by particle size optimization, control of the emittance of the container surfaces, inclusion of thin, highly reflective flakes, and use of highly absorbing coated powders and carbon. Strong et al.⁸ found desirable thermal conductivities could be obtained for insulating Dewars by using evacuated matts of glass fibers of proper size and orientation. They produced flat panel vacuum insulation that was equivalent to or better than normal Dewar flask insulation, and they noted these evacuated matts had a lower thermal diffusivity than any other insulation material.

Multilayered insulations employ radiation shields of the lowest emittance separated by spaces of low conductivity to reduce the radiation and solid conduction components. The net radiation transfer is proportional to the emittance of the surfaces and inversely proportional to the number of radiation shields between the two boundaries. Thus one often finds studies on various numbers of sheets and as a function of load to evaluate the terms that control heat transport in evacuated multilayer systems. Figure F-16 illustrates the heat flux reduction obtained by increasing the number of shields. The data points for 20 and 40 sheets exceed the expected value because the distortion of the shields under their own weight enhanced the solid conduction.

Fig. F-16. Effect of Number of Radiation Shields on Net Heat Flux. [Radiation shields: crinkled aluminized polyester film. Spacers: 1/8-by 1/8-in. (3 by 3 mm) mesh vinyl-coated fiber glass screen.] From Glaser et al.³²

While multilayer systems have been developed mostly for applications at cryogenic temperatures, high-temperature insulations can be obtained by changing the materials. Glaser et al.³² review some of the structures that have been so used. These include composites of graphite or glass fibers and gold sheets, stainless steel and Inconel honeycombs with Min-K*, and corrugated molybdenum sheets. Grunert et al.³³ present data on aluminum-glass and nickel-quartz systems that are capable of spanning the range 20 to 1000°C (68 to 1832°F). Apparent k values are presented for various loads and layer densities in this temperature range. As indicated earlier these foils are highly anisotropic, and considerable care must be exercised to obtain valid k values from the tests. Likewise, care is required in the design and installation of multifoil insulations to prevent thermal short circuits.

F-10 MOISTURE EFFECTS

Because liquid water conducts heat at a rate about 25 times that of air, the presence of water will reduce and often destroy the insulation value of a material. However, exact determinations of the effect of dampness are difficult because moisture will transfer from the warm to the cold regions of a sample during a test. Such transfer is shown in Fig. F-17 (a), with corresponding k values³⁴ given in Fig. F-17 (b), for an Ottawa silica sand of density 160 kg/m³ (10 pcf). Note the rapid change in k for low moisture contents, which in large measure is due to moisture transfer effects, which vary with the theoretical model assumed. In any case the latent heat of evaporation is transferred by diffusion of the water vapor in the air of the pore space. The "equivalent heat conductivity" of a damp sample due to the transfer of latent heat is shown in Fig. F-18 as a function of temperature, with the corresponding curves for water and air.³⁵ This shows that above 60°C (140°F) the rate of heat transfer through wetted pores is greater than pores filled with water! However, zones of varying moisture content will form, and this will lead to an overall effective conductivity less than calculated by the equation in Fig. F-18. This

* Trade name, Johns-Manville.

Fig. F-17. Moisture in Ottawa Sand. (a) Equilibrium moisture distribution: initial 2% and 4%-moist Ottawa sand; 160 kg/m^3 dry density; mean temperature, 297 K ; average temperature gradient 330 K/m , determined by hot plate apparatus. (b) Conductivities of Ottawa sand determined by guarded hot plate apparatus; mean temperature, 297 K ; temperature gradient 330 K/m . Reproduced from Pratt⁴ by permission of Academic Press.

Fig. F-18. Equivalent Conductivity, λ^* , of Porous Material (Conduction and Diffusion). Reproduced from Pratt⁴ by permission of Academic Press.

complicates any use of steady-state methods to measure the effect of moisture on the insulation. Table F-2 indicates Jacobs'³⁶ analysis of the variation of k with moisture content. Adams³⁷ presents a similar

Table F-2. Factors to Use for Moisture Content

Water Content, vol. %	1	5	10	20
Factor to correct k dry	1.3	1.75	2.10	2.55

series of water intensification factors, which in his words are *empirical, practical, plottable, and credible* for water in various building materials.

Becker³⁰ studied the effect of moisture on 1-ft² by 1-in.-thick (0.3 m² by 25 mm) samples of four insulations (Fiberglas,* corkboard, Foamglas,[†] and Isofoam) with cold faces near -15°C (5°F) and warm faces near 16°C (60°F) to ensure that the 0°C (32°F) plane was within the sample. The sealed samples were mounted in the walls of a test cubicle, and each had Gier-Dunkle heat flow meters, thermocouples, and blotter pad moisture sources. The conductance of these samples was measured during exposures lasting up to 600 days, and the wet-to-dry conductance

*Trade Name, Owens-Corning.

[†]Trade Name, Pittsburgh-Corning.

ratio showed very large increases due to the sensible and latent heat of the moisture. The effect of the moisture depends on its arrangement in the insulation and is minimal if concentrated on the cold side but large if ice bridges the system. He found after long-time exposures 16 vol % moisture increased heat transfer by 45% in Fiberglas, by 350% in cork-board, by 60% in Isofoam. In Foamglas, 8% moisture appeared to have increased heat transfer about 20%. These results were closer to the expected series system predictions than to those for a parallel system. Glaser³⁹ showed that the temperature and moisture distributions in hygroscopic walls with water vapor diffusion are nonlinear and that the relative humidity can reach 100% with continuous condensation unless a moisture barrier is installed.

Madsen⁴⁰ constructed a special guarded hot plate apparatus for studies on moist materials. His system allowed a constant moisture gradient to be established within the specimen by means of moist-air circulation on either side of the specimen. The relative humidity could thus be controlled throughout the specimen. The results obtained on soft fiberboard of dry density 240 kg/m^3 (15 pcf) are shown in Fig. F-19 for two sets of specimens, II and III adjacent to the hot plate and I and IV, to the cold plate. These results illustrate the effect of essentially stagnant moisture on k of a material. Experiments of a very practical nature such as this need to be done more extensively.

Ferro and Sacchi⁴¹ studied water vapor transmission through porous materials using a hot box system. Tests under isothermal conditions with 100% relative humidity on one side and 50% on the other yielded vapor permeabilities for expanded cork and expanded polystyrene shown in Fig. F-20. The permeability decreases nearly linearly with density for both materials. The effect of mean temperature and temperature gradient on the permeability of an expanded phenolic resin of density 56.3 kg/m^3 (about 3.5 pcf), as shown in Fig. F-21, is very pronounced.

Moisture obviously has a significant effect on the heat transmission characteristics of insulations. Since, as noted earlier, the ASTM test methods state that materials will be measured in the dry condition, this

effect is often glossed over by omission, but the increased k of moist insulations is a very real phenomenon that might cause a particular installation to fail to meet its design purpose.

Fig. F-19. The Dependence of the Thermal Conductivity of Soft Fiber Board on Relative Humidity. Samples II and III adjacent to hot plate, I and IV adjacent to cold plate. Reproduced from Madsen⁴⁰ by permission of Pergamon Press.

Fig. F-20. Vapor Permeability of Expanded Cork with Asphaltic Binder and of Expanded Polystyrene Versus Density at 100% Humidity on One Side and 50% on the Other and $t_1 = t_2 = 20^\circ\text{C}$. Reproduced from Ferro and Sacchi⁴¹ by permission of Pergamon Press.

Fig. F-21. Vapor Permeability μ^* of Expanded Phenolic Resin (Density 56.3 kg/m^3) Versus Mean Temperature $t_m = (t_1 + t_2)/2$ at Different Values of Temperature Gradient dT/dx but at Constant Vapor Pressure Difference $p_1 - p_2 = 12.9 \text{ mbar}$ (1.29 kPa). Reproduced from Ferro and Sacchi⁴¹ by permission of Pergamon Press.

F-11 REFERENCES

1. P. G. Klemens, "Chapter 1: Theory of the Thermal Conductivity of Solids," pp. 1-68 in *Thermal Conductivity*, Vol. 1, ed. by R. P. Tye, Academic Press, London, 1969.
2. C. Y. Ho, R. W. Powell, and P. E. Liley, *Thermal Conductivity of Selected Materials*, Nat. Stand. Ref. Data Ser. 8, National Bureau of Standards, Washington, D.C., November 25, 1966.
3. R. K. Williams and W. Fulkerson, "Separation of the Electronic and Lattice Contributions to the Thermal Conductivity of Metals and Alloys," pp. 389-456 in *Thermal Conductivity*, ed. by C. Y. Ho and R. E. Taylor, Plenum Press, New York, 1969.
4. A. W. Pratt, "Chapter 6: Heat Transmission in Low Conductivity Materials," Vol. 1, ed. by R. P. Tye, Academic Press, London, 1969.
5. S. Baxter, *Proc. Phys. Soc.* 48: 105 (1946).
6. Schuhmeister, *Ber. K. Acad. Weid.* 76: 283 (1877).
7. T. G. Godfrey, D. L. McElroy, and Z. L. Ardary, *Nucl. Technol.* 22: 94-107 (1974).
8. H. M. Strong, F. P. Bundy, and H. P. Bovenkerk, *J. Appl. Phys.* 31: 39 (1960).

9. E. A. Allcut, "Discussion," *Trans. Am. Soc. Mech. Eng.* 74: 967, 1952.
10. J. D. Verschoor and P. Greebler, *Trans. Am. Soc. Mech. Eng.* 74: 961 (1952).
11. D. Fournier and S. Klarsfeld, "Some Recent Experimental Data on Glass Fiber Insulating Materials and Their Use for a Reliable Design of Insulations at Low Temperatures," pp. 223-242 in *Heat Transmission Measurements in Thermal Insulations*, Am. Spec. Tech. Publ. 544, American Society for Testing and Materials, Philadelphia, 1974.
12. C. G. Bankvall, "Mechanisms of Heat Transfer in Permeable Insulation and Their Investigation in a Special Guarded Hot Plate," pp. 34-48 in *Heat Transmission Measurements in Thermal Insulators*, Am. Spec. Tech. Publ. 544, American Society for Testing and Materials, Philadelphia, 1974.
13. R.M.F. Linford, R. J. Schmitt, and T. A. Hughes, "Radiative Contribution to the Thermal Conductivity of Fibrous Insulations," pp. 68-84 in *Heat Transmission Measurements in Thermal Insulations*, Am. Spec. Tech. Publ. 544, American Society for Testing and Materials, Philadelphia, 1974.
14. C. M. Pelanne, "Experiments on the Separation of Heat Transfer Mechanisms in Low Density Fibrous Insulation," pp. 897-911 in *Thermal Conductivity*, ed. by C. Y. Ho and R. E. Taylor, Plenum Press, New York, 1969.
15. N. E. Hager and R. C. Steere, *J. Appl. Phys.* 38(12): 4663 (1967).
16. L. B. Davis and R. C. Birkebak, *J. Appl. Phys.* 44(10): 4583 (1973).
17. P. G. Klemens and I. N. Greenberg, *J. Appl. Phys.* 44(7): 2992 (1973).
18. V. Ferro and A. Sacchi, "An Automatic Plate Apparatus for Measurements of Thermal Conductivity of Insulating Materials at High Temperatures," pp. 737-760 in *Thermal Conductivity*, ed. by C. Y. Ho and R. E. Taylor, Plenum Press, New York, 1969.
19. J. P. Brazel and B. S. Kennedy, "Thermal Conductivity Measurements on Mullite and Silica REI for the Space Shuttle: Complementary Guarded Hot Plate and Radical Outflow Measurements," pp. 74-82 in *Advances in Thermal Conductivity*, ed. by R. L. Reisbig and H. J. Sauer, University of Missouri-Rolla, 1974.

20. E. J. Rolinski and G. V. Purcell, "Elevated Temperature Thermal Conductivity Measurements of Fibrous Insulations," p. V-A in *The Fifth Conference on Thermal Conductivity*, Vol. 1, Denver University, Denver, Colorado, 1965.
21. R. R. Pettyjohn, "Thermal Conductivity Measurements on a Fibrous Insulation Material," pp. 729-736 in *Thermal Conductivity*, Nat. Bur. Stand. Spec. Publ. 302, ed. by D. R. Flynn and B. A. Peavy, Jr., National Bureau of Standards, Washington, D.C., September 1968.
22. L. G. Reinhart, R. U. Acton, and A. B. Donaldson, "Heat Transfer in High Temperature Opacified Fiber Insulator," pp. 217-231 in *Advances in Thermal Conductivity*, ed. by R. L. Reisbig and H. J. Sauer, University of Missouri-Rolla, 1974.
23. G. W. Ball, R. Hurd, and M. G. Walker, "Urethane Rigid Foams: A Review of the Factors Affecting the Attainment and Retention of Optimum Thermal Conductivity and Their Significance in Service Applications," pp. 261-268 in *Heat Transfer*, Pergamon Press, 1971.
24. D. Fournier, "Comparative Study on the Main Physical Properties of Expanded Polystyrene Insulants," pp. 15-23 in *Progress in Refrigeration Science and Technology*, Vol. 2, Avi Publishing Company, Westport, Conn., 1973.
25. T. T. Jones, "The Effect of Thickness and Temperature on Heat Transfer Through Foamed Polymers," pp. 737-748 in *Thermal Conductivity*, Nat. Bur. Stand. Publ. 302, ed. by D. R. Flynn and B. A. Peavy, Jr., National Bureau of Standards, Washington, D.C., September 1968.
26. R. P. Tye, *J. Test. Eval.* 2(3): 176 (1974).
27. H. Steinle, "On the Behavior of Polyurethane-Foams in Refrigerator Cabinets," pp. 47-52 in *Progress in Refrigeration Science and Technology*, Vol. 2, Avi Publishing Company, Westport, Conn., 1973.
28. M. Dominguez, C. Fuster, and C. de Elvira, "Effects of Thermal Conductivity on the Behavior of Cellular Insulants," pp. 71-79 in *Progress in Refrigeration Science and Technology*, Vol. 2, Avi Publishing Company, Westport, Conn., 1973.

29. H. W. Godbee and W. T. Ziegler, "The Thermal Conductivity of MgO , Al_2O_3 , and ZrO_2 Powders to 850°C ," pp. 557-612 in *The 3rd Conference on Thermal Conductivity*, Vol. II, Sessions IV, V, VI, Oak Ridge National Laboratory, Oak Ridge, TN, October 1963.
30. R. L. Gorring and S. W. Churchill, *Chem. Eng. Prog.* 57(7): 53 (1961).
31. R. P. Tye, "Measurements of Heat Transmission in Thermal Insulations at Cryogenic Temperatures Using the Guarded Hot Plate Method," pp. 371-378 in *Progress in Refrigeration Science and Technology*, Vol. 1, Avi Publishing Company, Westport, Conn., 1973.
32. P. E. Glaser, I. A. Block, R. S. Lindstrom, F. E. Ruccia, and A. E. Wechsler, *Thermal Insulation Systems - A Survey*, NASA SP-5027, National Aeronautics and Space Administration, Washington, D.C., 1967.
33. W. E. Grunert, H. Morihara, R. L. Reid, and P. N. Massing, "Guarded Flat Plate Thermal Conductivity Apparatus for Testing Multi-Foil Insulations in the 20°C - 1000°C Range," pp. 658-672 in *Ninth Conference on Thermal Conductivity*, CONF-691002 (March 1970).
34. W. Woodside and J. B. Cliffe, *Soil Sci.* 87: 75 (1959).
35. O. Krischer, *Warme-u. Kältetechnik* 43: 2 (1941).
36. M. Jakob, *Heat Transfer*, Vol. 1, John Wiley & Sons, New York, 1949.
37. L. Adams, *ASHRAE J.* 16: 61-62 (October 1974).
38. W. Becker, *Moisture in Insulation*, Penn State University, College Park, 1965.
39. H. Glaser, "Temperature and Moisture Distribution in a Hygroscopic Wall with Water Vapour Diffusion," pp. 81-84 in *Progress in Refrigeration Science and Technology*, Vol. 2, Avi Publishing Company, Westport, Conn., 1973.
40. T. L. Madsen, "Modified Guarded Hot Plate Apparatus for Measuring Thermal Conductivity of Moist Materials," pp. 309-319 in *Heat Transfer*, Pergamon Press, 1971.
41. V. Ferro and A. Sacchi, "On the Water Vapor Transmission through Porous Materials," pp. 253-260 in *Heat Transfer*, Pergamon Press, 1971.

INTERNAL DISTRIBUTION

1-2. Central Research Library	50. H. E. McCoy
3. Document Reference Section	51-53. D. L. McElroy
4-5. Laboratory Records	54. C. J. McHargue
6. Laboratory Records, ORNL RC	55. J. T. Meador
7. ORNL Patent Office	56. W. R. Mixon
8. Z. L. Ardary	57. J. P. Moore
9. D. S. Billington	58. J. C. Moyers
10. R. S. Carlsmith	59-158. C. J. Oen
11. F. L. Culler	159. H. Postma
12. J. E. Cunningham	160. M. W. Rosenthal
13-26. R. G. Donnelly	161. J. L. Scott
27. W. P. Eatherly	162-164. V. J. Tennery
28. K. E. Farrell	165. D. B. Trauger
29. W. Fulkerson	166. T. N. Washburn
30. H. W. Godbee	167. G. C. Wei
31-33. T. G. Godfrey	168. J. R. Weir, Jr.
34. V. O. Haynes	169. R. K. Williams
35-37. M. R. Hill	170. C. S. Yust
38. E. C. Hise	171. S. H. Jury (consultant)
39. H. W. Hoffman	172. W. C. Leslie (consultant)
40. F. J. Homan	173. John Moteff (consultant)
41. S. I. Kaplan	174. Hayne Palmour III (consultant)
42. O. A. Kelley	175. J. W. Prados (consultant)
43-45. J. O. Kolb	176. N. E. Promisel (consultant)
46. T. G. Kollie	177. G. V. Smith (consultant)
47. J. E. Mack	178. D. F. Stein (consultant)
48. W. R. Martin	179. E. E. Stansbury (consultant)
49. R. W. McClung	180. W. C. Turner (consultant)
	181. D. W. Yarbrough (consultant)

EXTERNAL DISTRIBUTION

182. R. A. Alford, Amspec, Inc.
183. Charles W. Almand, United States Gypsum Co.
184-213. R. W. Anderson, Energy Research Development Administration
214. David Azbill, Shell Oil Co.
215. John Baer, 225 East 46th St., New York, N.Y. 10017
216. W. T. Bakker, Chief, Materials Division of Fossil Energy Research, ERDA
217. Geroge Barnett, Stone & Webster Engineers
218. John Barnhart, Thermal Insulations Mfg. Association
219. E. A. Barrington, Shell Oil Co.
220. Ralph Bernstein, The Mead Corp.
221. J. R. Blevins, Research & Technical Support Division, ORO, ERDA
222. W. C. Bohling, Babcock & Wilcox Co.
223. John A. Bonar, The Carborundum Co.

- 224. Denis Brosnan, General Refractories Co.
- 225. W. Browning, Cabot Corp.
- 226. Nile V. Bucher, Incell Corp.
- 227. Charles P. Buhsmer, Horizons, Inc.
- 228. Carl E. Burley, Reynolds Metal Co.
- 229. Sheldon Cady, 382 Springfield Ave., Summit, NJ 07901
- 230. W. C. Carroll, Building Research, U.S. National Bureau of Standards
- 231. Arthus L. Chart, Harbison-Walker Refractories
- 232. J. L. Cook, Fiber Materials, Inc.
- 233. Charles Coppin, Southern California Edison Co.
- 234. William Crawford, El Paso Natural Gas Co.
- 235. E. F. Cusick, Jr., Rock Wool Manufacturing Co.
- 236. David Davia, Public Service Co. of Colorado
- 237. James A. Davies, Texaco, Inc.
- 238. Tom Deloach, Mobil Oil Corp.
- 239. Gery Deugaw, Plibrico Co.
- 240. F. Dubin, Dubin-Mindell-Bloom Assoc. P.C.
- 241. D. M. Durdan, Mobay Chemical Corp.
- 242. A. D. Fentzke, Emhart Corp.
- 243. D. R. Flynn, U.S. National Bureau of Standards
- 244. David G. Frantz, Amoco Oil Co.
- 245. Geoffrey Frohnsdorff, National Bureau of Standards
- 246. Edward A. Fusakio, Exxon Chemical Co.
- 247. Hollis L. Garren, Christy Firebrick Co.
- 248. R. W. Gerrish, Pittsburgh Corning Corp.
- 249. C. Joe Golden, Tennessee Technological University
- 250. L. D. Graves, Eagle-Picher Industries, Inc.
- 251. M. Gyogyoge, Systems Analysis Office, ERDA
- 252. Bernie H. Hamling, Zircar Products, Inc.
- 253. Douglas Harvey, ERDA
- 254. Sanford H. Heard, Jr., Owens/Corning Fiberglas
- 255. Siegfried Hecker, Ebasco Services, Inc.
- 256. W. W. Heinrich, Phillips Petroleum Co.
- 257. Stuart P. Hepburn, ICI United States, Inc.
- 258. Jerome G. Hust, National Bureau of Standards
- 259. Art W. Johnson, NAHB Research Foundation, Inc.
- 260. Winston Johnson, El Paso Natural Gas Co.
- 261. E. A. Joy, Pennsylvania State University
- 262. Keith Kappmeyer, U.S. Steel Corp.
- 263. M. L. Kasbohm, Linde Division
- 264. Ralph C. Kirby, Bureau of Mines
- 265. Richard Kirby, U.S. National Bureau of Standards
- 266. Peter Kromayer, Bethlehem Steel Corp.
- 267. R. M. Lander, 1320 W. 28th St., Minneapolis, Minn. 55408
- 268. Dennis H. Larson, Institute of Gas Technology
- 269. Jerry Leighton, ERDA
- 270. J. A. Lenhard, Director, Research and Technical Support Division, ORO, ERDA
- 271. Paul Leung, Bechtel Power Corp.
- 272. Charles Lindsay, Tennessee Valley Authority
- 273. Larry Long, Babcock & Wilcox Corp.
- 274. C. F. Lucks, 1858 W. Lane Ave., Columbus, OH 43221

275. Dick Ludwig, Hammermill Paper Co.
276. Ian MacFarlane, MacFarlane & Co., Inc.
277. Paul S. Maco, Spraycraft Corp.
278. R. W. Maier, Gulf Research & Development Co.
279. Stan Mathews, Rockwool Industries, Inc.
280. William Mead, Ferro Corp.
281. Peter J. Meehan, Pittsburgh Corning Corp.
282. Ross Meriweather, Ross F. Meriweather and Assoc., Inc.
283. Paul D. Messner, Resco Products, Inc.
284. Herbert A. Moak, E. I. duPont deNemours
285. John Mochel, Philadelphia Electric Co.
286. John Moskowitz, Philadelphia Electric Co.
287. James Mossberg, Exxon Oil Co.
288. Randy E. Muchow, Carborundum Co.
289. Larry Neusslein, Air Products
290. Frank Oliver, Public Service Co. of Colorado
291. W. L. Olmsted, Celutex Corp. of Jim Walter, Inc.
292. M. N. Orr, International Vermiculite Co.
293. Charles M. Pelanne, Johns-Manville Corp.
294. W. W. Pitkin, Certain-Teed Products Corp.
295. Robert H. Poirier, Battelle Columbus Laboratories
296. Ernest Powell, Union Carbide Corp.
297. Frank Powell, National Bureau of Standards
298. William A. Pugh, Jr., Viamasco Corp.
299. John T. Reding, Dow Chemical USA
300. Robert Reed, John Zinc Co.
301. R. H. Rein, Linde Research
302. J. F. Reynolds, Carborundum Co.
303. Robert Rinehart, York Research Corp.
304. R. B. Rosenberg, Institute of Gas Technology
305. Roger W. Roth, Owens Corning Fiberglas Corp.
306. M. Savitz, ERDA
307. Dave Schaidler, Forty-Eight Insulations, Inc.
308. R. K. Schlafly, Arthur G. McKee and Co.
309. J. Richard Schorr, Battelle Columbus Laboratories
310. Robert Scott, Commonwealth Edison Co.
311. Charles E. Semler, Refractories Research Center
312. Clift J. Shirliffe, National Research Council of Canada
313. R. L. Shultz, Armco Steel Corp.
314. Chester P. Smolenski, Pittsburgh Corning Corp.
315. Irving Snyder, Dow Chemical Co.
316. M. Jack Snyder, Battelle Columbus Laboratories
317. L. T. Solari, Owens/Corning Fiberglas
318. Louis D. Sorrentino, Johns-Manville Corp.
319. P. F. Stanley, Monsanto Co.
320. R. D. Steif, Chemical and Plastics
321. Thomas Stein, Badger America, Ind.
322. D. F. Stock, Harbinson-Walker Refractories
323. Joe Stringer, Duke Power Co.
324. Chock Sui, National Bureau of Standards
325. George B. Tarbutton, Thermon Corp.

- 326. Louis J. Trostel, Norton Co.
- 327. Bradford S. Tucker, Refractories Institute
- 328. Ron P. Tye, Dynatech R/D Co.
- 329. J. D. Ueber, U.S. Gypsum Co.
- 330. C. R. Vander Linden, Johns-Manville Corp.
- 331. W. W. VanWyngarden, A.P. Green Refractories Co.
- 332. Jack D. Verschoor, Johns-Manville Corp.
- 333. W. J. Wartan, Sargent and Lundy, Inc.
- 334. Mr. Weber, Fibreboard Corp.
- 335. W. T. Wells, Gulf Oil Co.
- 336. Thomas E. Werkema, Dow Chemical Co.
- 337. K. E. Wilkes, Battelle Columbus Laboratories
- 338. Foster C. Wilson, Owens/Corning Fiberglass
- 339. C. E. Winters, Union Carbide Corp. Consolidated Offices
- 340. R. K. Woodruff, Refractory Products Co.
- 341. Neil Young, International Paper Co.
- 342. USERDA, Oak Ridge Operations Office, Research and Technical Support
Division
- 343-369. USERDA, Technical Information Center